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DOC. NO.
NARF-61-39
FZK-9-170

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SHIELD PENETRATION PROGRAMS C-17 AND L-63

U. S. AIR FORCE

Nuclear Aerospace Research Facility
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GENERAL DYNAMICS FORT WORTH

DOC. NO.
NARF-61-39
FZK-9-170

DOC. NO.
NARF-61-39T
FZK-9-170

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GENERAL DYNAMICS FORT WORTH

29 DECEMBER 1961

SHIELD PENETRATION PROGRAMS C-17 AND L-63

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SECTION I, TASK I, ITEM 6
OF FZM 2004 A

CONTRACT
AF 33(600) 38946

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ABSTRACT

Two programs are described which have been coded for the IBM-704 (and are compatible with the IBM-7090). The programs calculate the neutron and/or gamma spectra, heat generation rate, and/or dose rate at each of a group of point detectors, due to each of a group of point sources. The sources may be divided into sets, with each set having a unique source spectra. In addition to the above calculation, the spectrum, heating rate, and/or dose rate for each detector, summed over each source-point set and over the entire source group may be computed. The two programs are similar, both computationally, and as regards input and output information, excepting for the complexity of the problem geometries acceptable to the programs.

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I INTRODUCTION

The two shield-penetration programs (C-17 and L-63) described here were coded to take advantage of the data given in Reference 1 as well as to allow the computation of the heat generation rates in a shield system due to the fast-neutron and gamma-ray reactor leakage spectra.

These programs are the latest generation in the continued development of moments-method shield-penetration programs conducted at the Nuclear Aerospace Research Facility (NARF) at General Dynamics/Fort Worth (GD/FW). These methods were first used at NARF to analyze data from the Nuclear Test Aircraft flights. The methods were also used to code shield-penetration programs for the IBM-701 and IBM-704 in order to compute fast-neutron and gamma-ray spectra and dose rates in shield systems described by a geometry system similar to the simple geometry routine described in Section II. This family of programs has been developed around the following basic concepts:

Moments Method - This method is based upon the differential energy spectra calculated by the Nuclear Development Corporation of America (NDA) for a point isotropic source in an infinite medium (Ref. 2). The data represents a moments-method solution of the fast-neutron and gamma-ray transport equation. A detailed description of the use of these data is given in Reference 3. This method implies that the only portion of the system affecting dose rate (or spectra, or heat generation rate) at a detector due

to a point source a distance r from the detector is that portion of the system lying on the line of sight between the source and the detector; hence, the techniques discussed below are required in the use of this method.

The Stepping Point Method - This is an iterative method of determining the intercepted distances between two points. In this procedure, an iterative scheme is used to "step" a point through the volumes of the system, and, after each step, tests are performed to determine whether a boundary of the volume has been crossed. The intercepted distance is then determined by the number of steps and the length of each step taken in each volume. A discussion of the basic ideas and methods used in adapting this concept to computer programs is given in Reference 4.

Distributed Source - The moments-method data used in the calculations are for point isotropic sources; thus, it is necessary to approximate the leakage from a reactor or other source by a set of point sources. Each of these sources represents the radiation born in an elemental volume containing a point so that an integration of source points over the source volume must equal the total radiation generated by the source.

The new programs differ from the earlier versions principally in the following new features:

1. Direct computation of radiation heat generation rates,
2. Greater resolution of gamma-ray energy spectra,
3. Capability for testing more complex geometries.

The logic involved in the programed solution of the spectral and heat and dose equations as well as the equations themselves are described in Section II, and the instructions and data formats required in order to use these programs are given in Section III. Four appendices contain:

1. A list of the symbols used in the flow diagrams for the two programs,
2. Derivations for the neutron flux-to-heat conversion coefficients,
3. Tables of data for the materials libraries, and
4. Neutron reference-material comparison.

II PROGRAM LOGIC

Each penetration program is divided into three subprograms, namely: geometry, gamma, and neutron routines. The gamma and neutron routines are the same in both programs. The geometry routine of the first code (C17) is restricted to geometries composed of frustra of rectangular pyramids and coaxial cylinders and their annuli. The geometry routine of the second program (L-63) accepts a more general class of solids, specifically, cylinders and their annuli which are defined about arbitrary axes, sectors of these cylinders, and frustra of pyramids whose bases are quadrilaterals. In addition, using the spherical option, spheres, hollow spheres or hemispheres, spherical sectors, and spherical sectors with one or two ends cut off may be defined for L-63. This code also accepts regions within regions and regions within regions within regions in which the geometry types can be varied. These routines are described in the following sections.

2.1 Geometry Calculation

The intercepted distances in each material along the line-of-sight joining each source point with each receiver point are required in the gamma and neutron routines. The purpose of the geometry routine is to compute this information from data which describe the geometry of the system and the location of source points and detector points.

The method described here is not the classical method of determining the intercepted distances between two points, rather

it is an iterative method based upon the stepping-point concept. Using this method, a point is moved along a line in steps of known length. The stepping point $\bar{P}$ (with components x_p, y_p, z_p) is originally coincident with the source point $\bar{S}$ (with components x_s, y_s, z_s). A step along the line-of-sight toward the detector point is accomplished by adding a constant K times the direction cosine vector $\bar{L}$ to the stepping-point vector. Thus,

$$\overline{P} \longrightarrow \overline{P} + K\overline{L},$$

(The above expression should be read as: "$\bar{P}$ is replaced by $\bar{P} + K\bar{L}$".) Or component wise,

$$x_p \longrightarrow x_p + K\ell_1$$

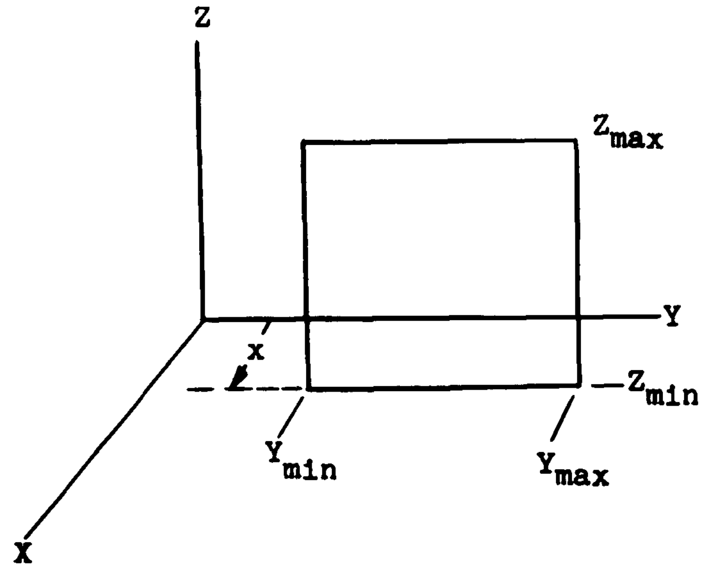
$$y_p \longrightarrow y_p + K\ell_2$$

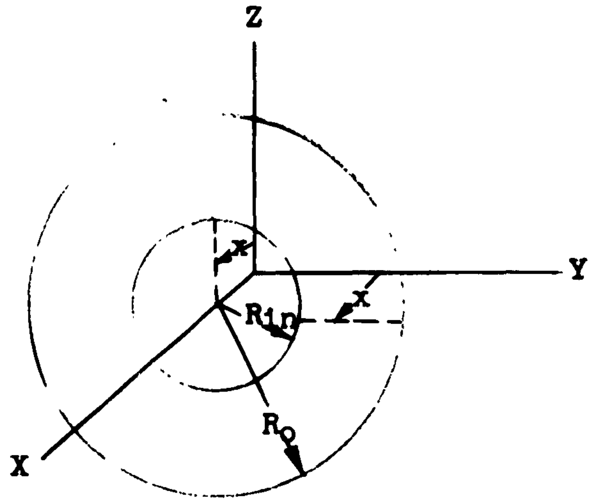
$$z_p \longrightarrow z_p + K\ell_3$$

where ℓ_1, ℓ_2, ℓ_3 are the direction cosines of the source detector line-of-sight in the x,y, and z directions, respectively.

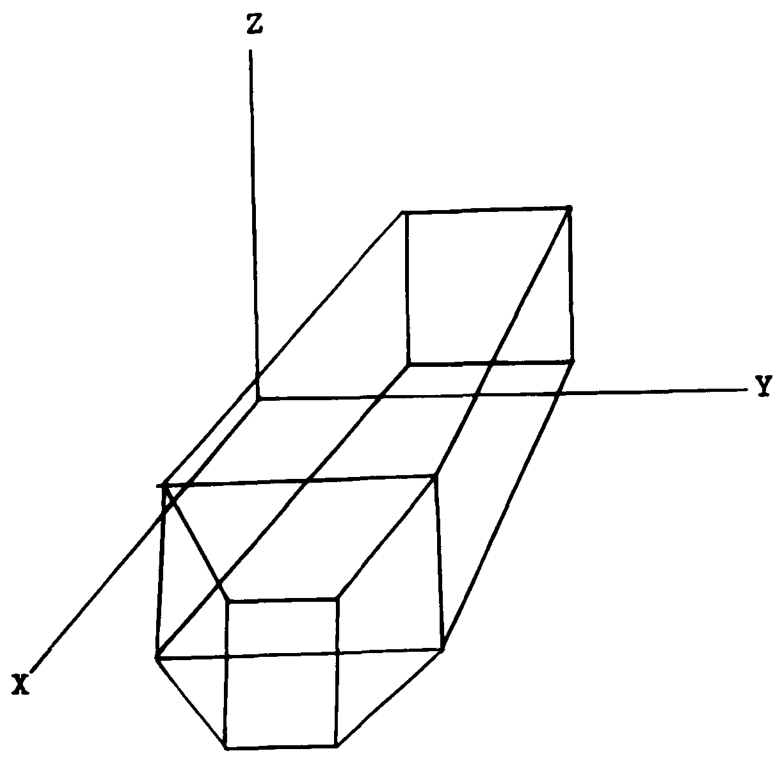
The stepping point must be identified as being in some particular geometric volume before the first step is taken. Then, after each step, the stepping point must be tested again to ascertain whether it is still in the same volume. Once a boundary has been crossed, a vernier effect may be achieved by taking one step back, reducing the step size, and repeating the procedure until the difference between the stepping-point position and the detector-side boundary of the volume is less than the boundary uncertainty parameter, K_{min}.

The method of defining the geometric volumes for these programs rests on the concept of an x-plane. As used here, for a given Cartesian coordinate system, an x-plane is a set of numbers sufficient to define a plane area perpendicular to the x-axis of the system plus the x-coordinate of this area, or the areas, depending upon the context. Two examples of x-planes are shown in the sketches below.





The first of these shows a rectangular area, hence the x-plane consists of the set x, Y_{min}, Y_{max}, Z_{min}, Z_{max}, or, the rectangular area at x bounded by the last four of the above numbers. The second is a circular annulus, so that the x-plane consists of the set x, R_{in}, R_o, or the annular area at x bounded by R_{in} and R_o. For these programs, a volume is defined by two or more x-planes of the same type, and that portion of the volume surface which is not coincident with one of the defining x-planes is defined from either a linear interpolation or, for the spherical option, a particular second order interpolation between similar points of adjacent x-planes. A volume defined by rectangular x-planes is sketched below. This volume is defined by three x-planes of the type depicted in the first example above.



The class of "spherical volumes" acceptable to the complex-geometry routine consists of those whose centers lie on the x axis (see sketch). Thus, the equation for this class is

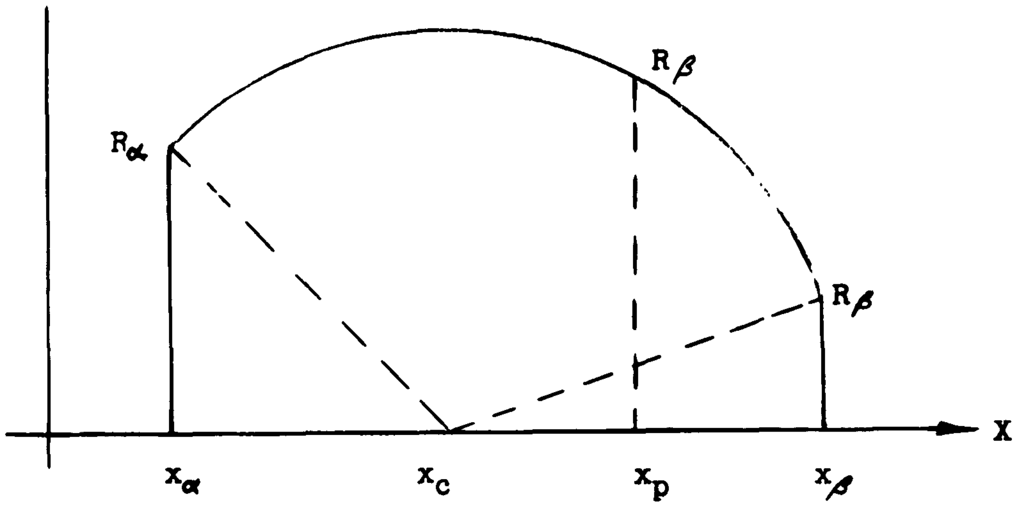
$$(x-K)^2 + Y^2 + Z^2 - \rho^2 = 0,$$

where

K is the x-coordinate of the center, and

ρ is the radius of the sphere.

The interpolation formula is derived below.



Assume a portion of a sphere is to be defined with center at x_c, radius ρ, and truncated at x_α and x_β. Then $R_\alpha = \sqrt{\rho^2-(x_\alpha - x_c)^2}$ and $R_\beta = \sqrt{\rho^2-(x_\beta - x_c)^2}$. Then, for some x_p, such that $x_\alpha \leq x_p \leq x_\beta$, the point R may be found in terms of x_p, x_α, R_α, x_β, and R_β by successive application of the Pythagorean Theorem:

$$R^2 = \rho^2-(x_p - x_c)^2$$
$$R_\alpha^2 = \rho^2-(x_\alpha - x_c)^2$$
$$R_\beta^2 = \rho^2-(x_\beta - x_c)^2$$

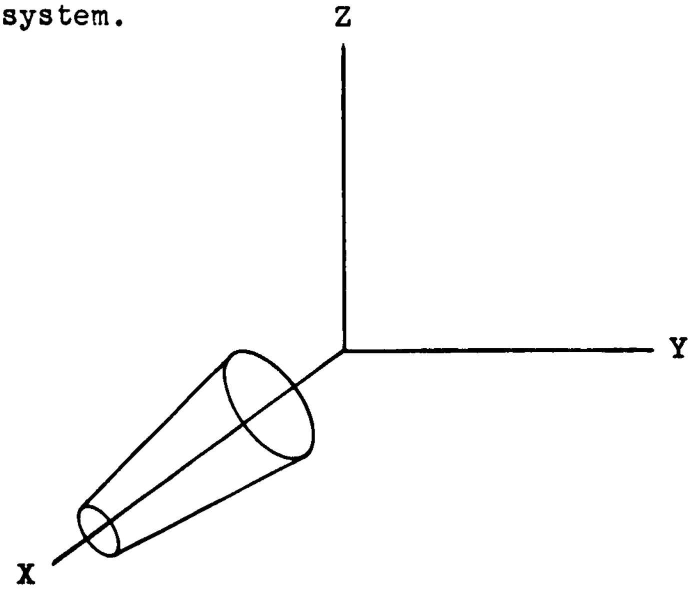
Combining the above equations gives:

$$R^2 = \frac{(R_\alpha^2 + x_\alpha^2)(x_\beta - x_p) - (R_\beta^2 + x_\beta^2)(x_\alpha - x_p)}{x_\beta - x_\alpha} - x_p^2$$

or

$$R = \sqrt{\frac{(R_\alpha^2 + x_\alpha^2)(x_\beta - x_p) - (R_\beta^2 + x^2)(x_\alpha - x_p)}{x_\beta - x_\alpha} - x_p^2} \quad .$$

A volume defined by cylindric x-planes of the type depicted in the second example is shown below. It should be noted that the axis of symmetry of this figure is coincident with the x axis of the coordinate system used to define the volume. This restriction holds for the definition of all volumes used in the programs, excepting those composed of x-planes of the type shown in the first example above and the complex Cartesian x-planes for the complex-geometry program. Different coordinate systems may be used for different sets of volumes in the defined region by defining them with respect to a reference system.

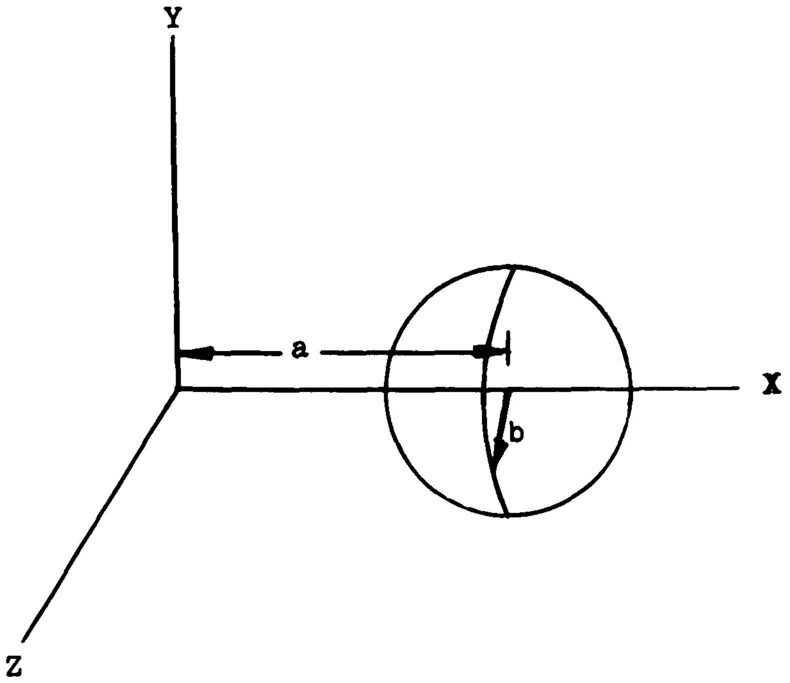


Examples of spherical volumes which may be defined by a coordinate type (CT) of -2 or -3 where the required x-plane parameters are:

1. Sphere with center at $x = a$, and radius b:

CT = -2 (simple cylindric x-planes)

First x-plane: $x = a - b$, $R_{in} = 0$, $R_o = 0$
Second x-plane: $x = a + b$, $R_{in} = 0$, $R_o = 0$



2. Sector of a hollow sphere or spherical shell with center at a, inner radius b_1 and outer radius b_2, with the sector occupying the azimuthal anglular range (in the yz-plane) ϕ_1 to ϕ_2 (see sketch on next page):

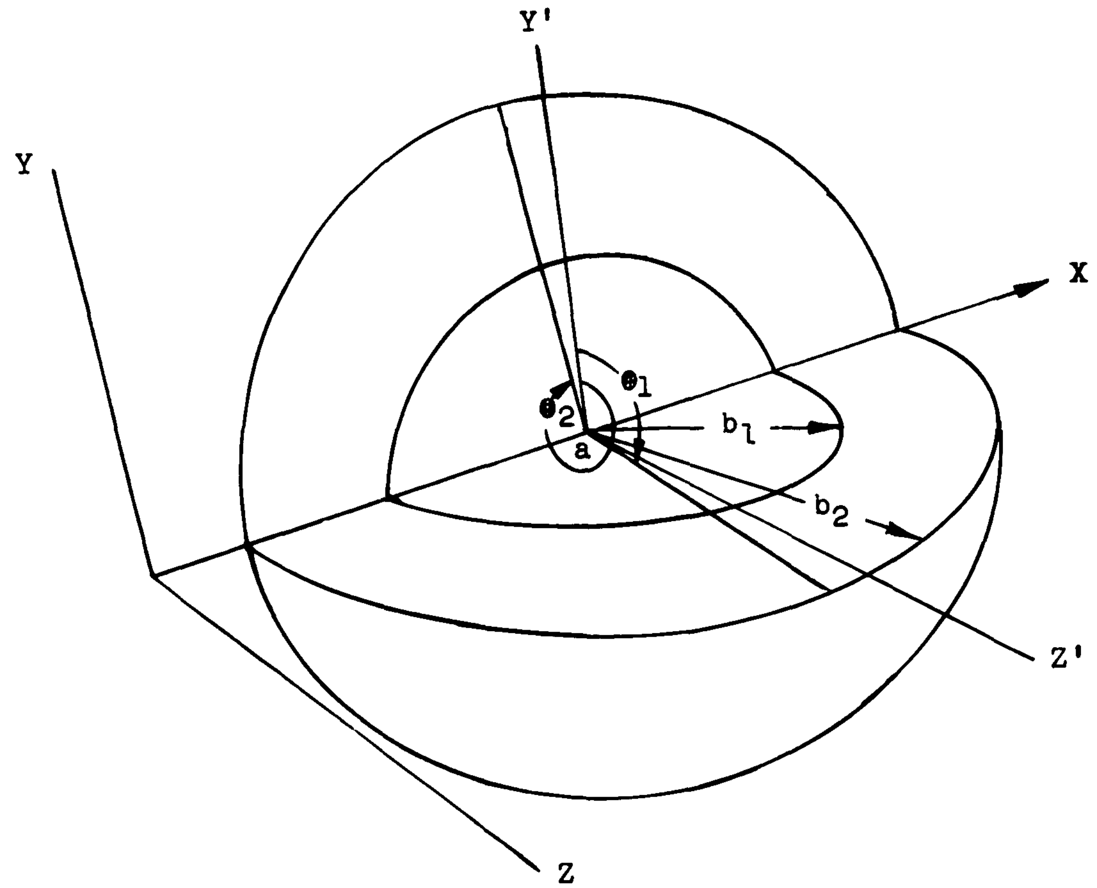
CT = -3 (complex cylindric x-planes)

First x-plane: $x = a - b_2$, $R_{in} = 0$, $R_o = 0$, $\theta_1 = \phi_1$, $\theta_2 = \phi_2$

Second x-plane: $x = a - b_1$, $R_{in} = 0$, $R_o = \sqrt{b_2^2 - b_1^2}$, $\theta_1 = \phi_1$, $\theta_2 = \phi_2$

Third x-plane: $x = a+b_1$, $R_{in} = 0$, $R_o = \sqrt{b_2^2-b_1^2}$, $\Theta_1 = \phi_1$, $\Theta_2 = \phi_2$

Fourth x-plane: $x = a+b_2$, $R_{in} = 0$, $R_o = 0$, $\Theta_1 = \phi_1$, $\Theta_2 = \phi_2$



Note: The primed coordinate system is shown to illustrate the method of measuring the azimuthal angles θ_1 and θ_2. This system is merely a translation along the x axis of the unprimed system.

For clarity and conciseness, the following terms are used in describing both of the geometry routines, although those terms preceded by an asterisk are used for the complex geometry only. The symbols used in the geometry flow diagrams are described in Appendix A.

1. x-plane - this concept is defined above.

2. element - a volume defined by two adjacent x-planes.

3. volume - a set of adjacent elements defined by a consistent set of x-planes.

Three types of volumes are defined for the complex-geometry routine:

a. *subregion - a volume containing only one material and containing no other volume.

b. *region - a volume which may contain an arbitrary number of subregions of various materials and has associated with it a base material which occupies that portion of the region not occupied by subregions.

c. *master region - a volume which may contain up to 10 regions of various kinds and has associated with it a base material similar to that for regions.

Note: All regions should be contained in a master region, and all subregions should be contained in a region.

For the simple-geometry routine, only one type of volume is defined, and it is called a region. For this routine there is no volume containment.

4. dummy volume - the routine requires that every part of the problem space have some material associated with it. The dummy volume is not a defined volume in the sense that a number of x-planes are required to delineate this volume. Rather, it is assumed that the dummy volume occupies all space not occupied by other defined volumes. For the complex-geometry routine, the last master region defined in the geometric input must be the dummy volume, while for the simple-geometry routine, the last region is the dummy volume.

5. source-detector line - the straight line connecting a source point and a detector. (If this line has direction, as in computing the direction cosines of this line, the sense is from source to detector.)

6. segment - the penetration distance along the source-detector line through one volume multiplied by the density of the material of the volume, or for two or more volumes of the same material which are either adjacent, or separated only by void, the associated segment is the sum of the products of the penetration distance through each volume and the density of the material therein. (No segment or portion thereof corresponds to a void volume.)

That is, if $M_{i-1} \neq M_i \neq M_{i+1}$, and M_{i-1}, M_i, and M_{i+1} are non-zero where M_i is a number used to identify a material in the i^{th} volume along a source-detector line and $M_i = 0$ if the material is a void, the segment W_i is given by

$$W_i = t_i \rho_i ,$$

where ρ is the density of the material, and t is the thickness (along the source-detector line).

If $M_i = M_{i+2}$, and $M_{i+1} = 0$ (void), then

$$W_i = (t_i \rho_i + t_{i+2} \rho_{i+2}).$$

7. detector-side boundary, source-side boundary (of a volume) - the two adjacent intersections of the source-detector line and the volume surface, the source-side boundary being closest to the source point.

8. *envelope - for Cartesian volumes - the smallest rectangular parallelepiped which contains the volume in question. This envelope is described by two x-values, two y-values, and two z-values.

for cylindrical volumes - the smallest volume, described by two x-planes of the same type used to define the volume, which contains the volume.

9. *base material - for a volume - that material which fills the volume, except for the space occupied by subvolumes.

- for a problem - that material in which the system is assumed to be immersed. (This is the material associated with the dummy volume.)

2.1.1 Simple-Geometry Routine

2.1.1.1 Volumes Acceptable to the Routine. Each volume used to describe the system being studied should be defined by a set of x-planes of one and only one of the following types (as illustrated in Figure 2-1).

1. Simple Cartesian. The defined area is a rectangle whose sides are parallel to the y and z axes. The numbers necessary to define the area are x_p, Y_{min}, Y_{max}, Z_{min}, and Z_{max} (Fig. 2-1).

   Restrictions: Orientation - $Y_{min} \leq Y_{max}$ and $Z_{min} \leq Z_{max}$

2. Simple Cylinder. The defined area is a circular annulus. The numbers necessary to define the area are x_p, R_{in}, and R_o (Fig. 2-1).

   Restrictions: Orientation - All cylinders must be defined to be coaxial with the x-axis of the coordinate system used to define the system and $R_{in} \leq R_o$.

2.1.1.2 Method Outline. The segments W_i and the associated material identification numbers M_i are evaluated using the stepping-point described in Section I. The overall flow diagram for the simple geometry code (C-17) is shown in Figure 2-2. A flow diagram for the geometry routine is shown in Figure 2-3. Nomenclature is given in Appendix A.

For a given detector point, all W_i, M_i, and the number of segments, i_{max} are determined for each source point by the method

(increasing x is out of the paper)

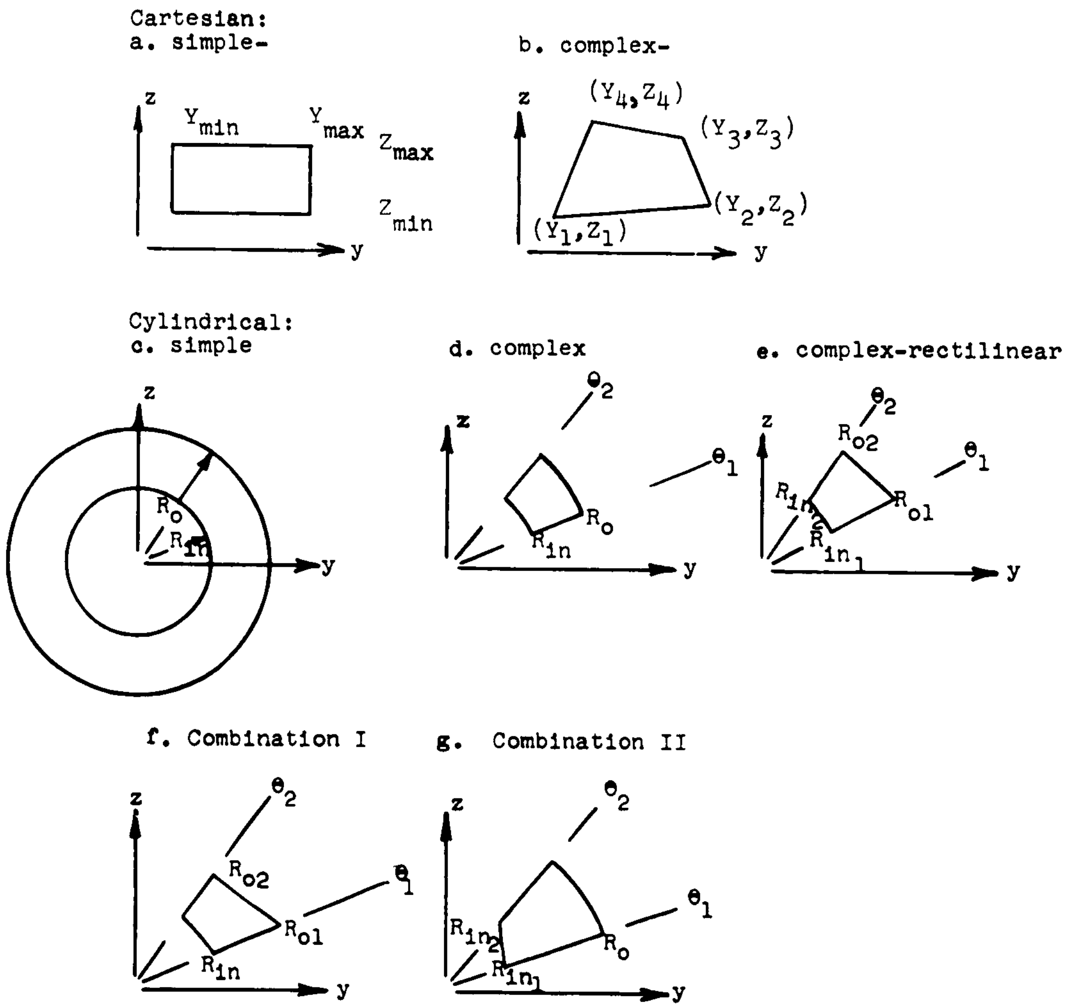


FIGURE 2-1. X-PLANE CROSS SECTIONS

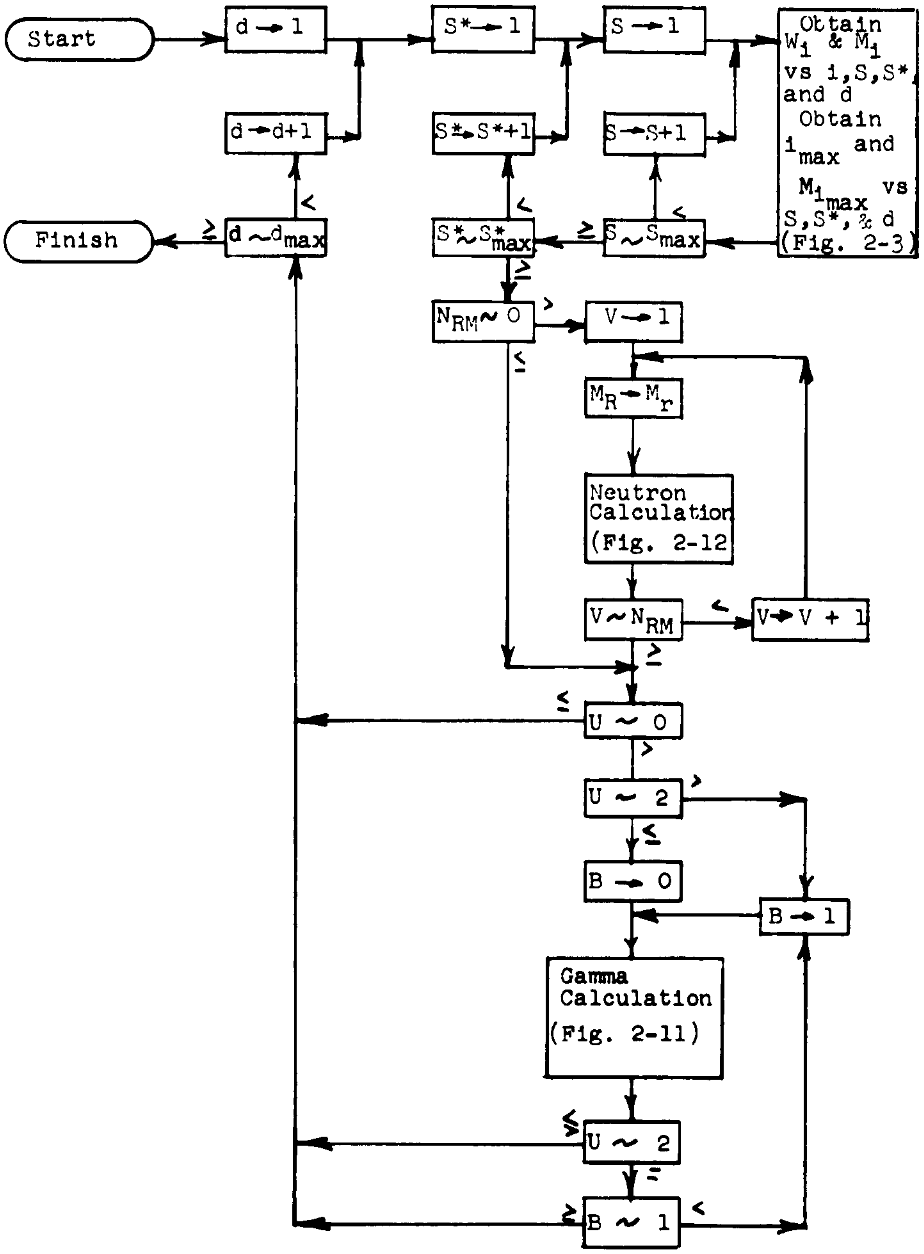


FIGURE 2-2. SIMPLE-GEOMETRY OVERALL FLOW DIAGRAM

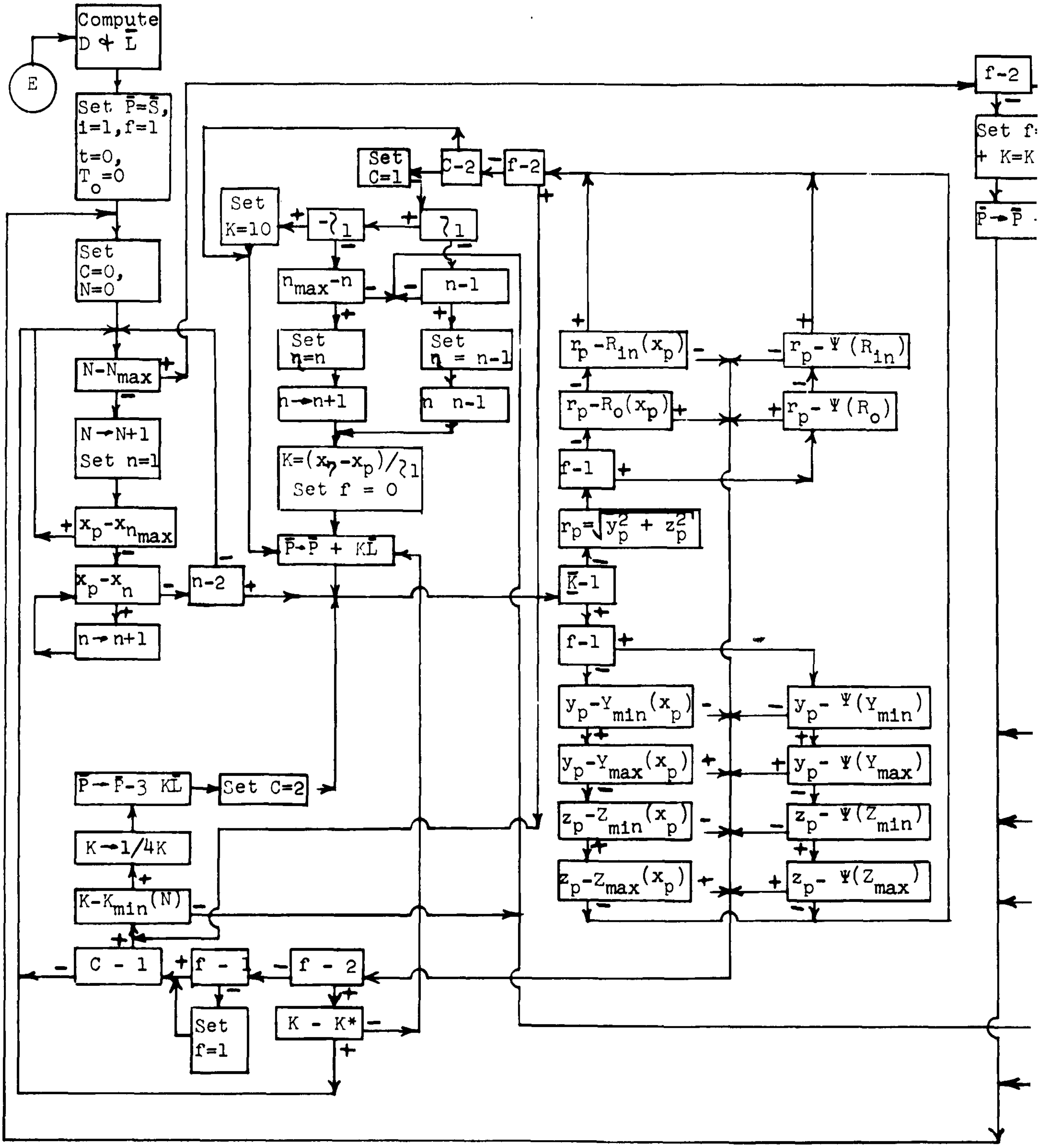
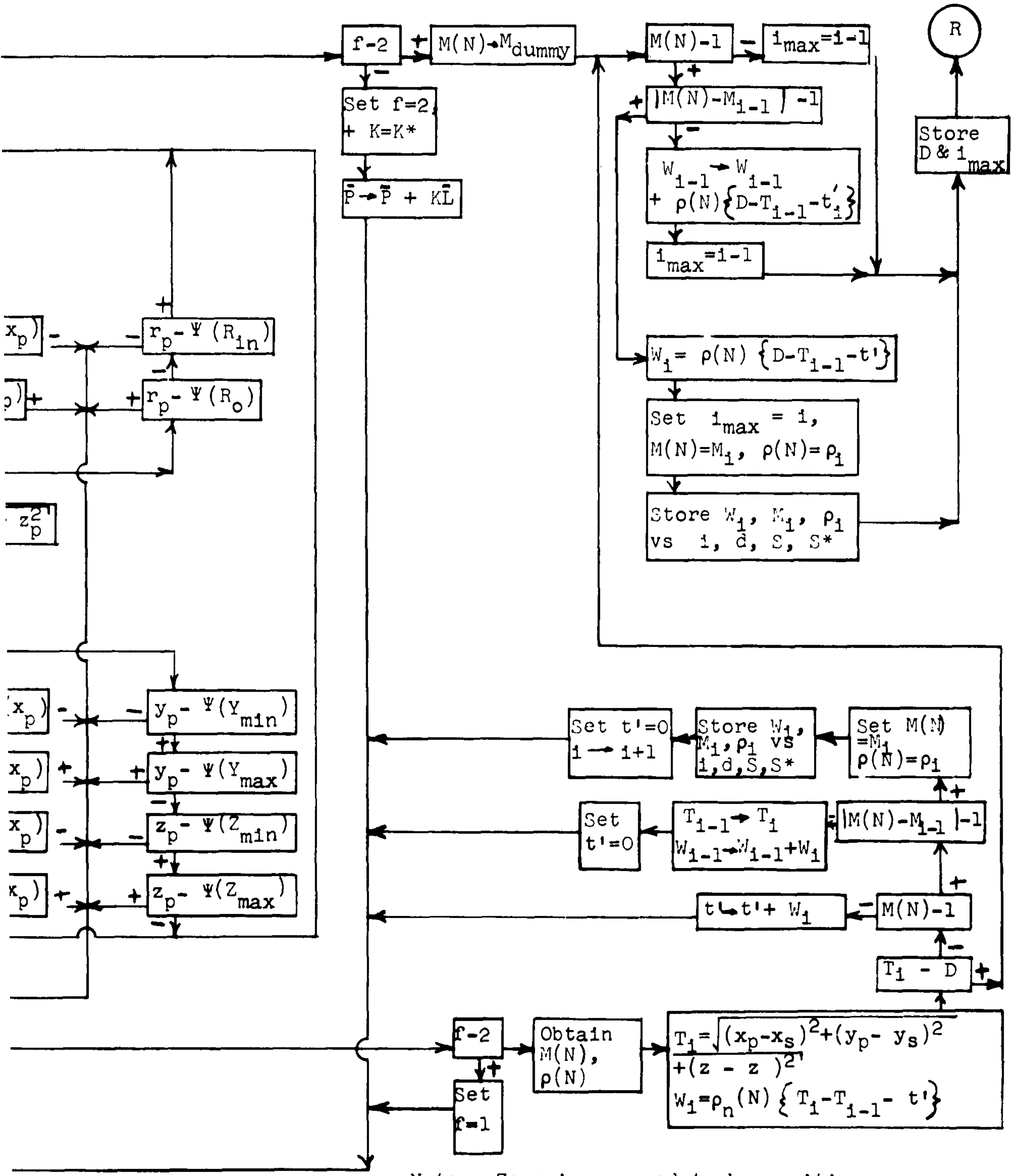


FIGURE 2-3. SIMPLE-GEOMETRY ROUTINE



Note: Zero is assumed to be positive.

2-3. SIMPLE-GEOMETRY ROUTINE

2

outlined below. At this point, the neutron and/or gamma calculations are made, and this step is repeated until the calculations are made for each detector point.

1. A source point is chosen; then the source-detector distance, D, and the direction cosines of the line from the source to the detector are computed, and the stepping point is taken to be the source point.
2. The stepping point is tested against each region to determine the region in which the stepping point lies.
3. If the stepping point is found to lie within one of the defined volumes, the detector-side boundary is found by the method outlined above and the stepping point is put past the detector-side boundary of this volume but within K_{min} of the boundary. Then the distance between the source-side and detector-side boundaries is taken to be a tentative segment. The material number of this volume is found, and if it is non-zero (material number zero is taken to be void), the material number is tested against the last non-zero material number. If the material numbers are equal, the materials are the same, and the tentative segment is multiplied by the appropriate density and added to the last segment. If the material numbers are not equal, the materials are different, and the tentative segment is multiplied by the appropriate density and stored as a

segment W_1, along with the corresponding material number M_1 and segment counter i. If the material number is zero, the tentative segment is not used as a segment or a portion thereof.

4. Steps 2 and 3 are repeated until either

   a. the stepping point is found to have passed the detector - in this case, the distance between the source-side boundary and the detector is called a tentative segment, which is treated as in Step 3 above, and the program goes to Step 1, unless the source points have been exhausted, or

   b. the stepping point is found to be in an undefined region (the dummy material) by testing against all defined regions (Step 2) and finding the stepping point in none of them - in this case, the stepping point is taken to be at the detector, and the distance between the last detector-side boundary and the dectector is taken to be a tentative segment and is treated as in Step 3. Then the program goes back to Step 1 unless the source points have been exhausted.

2.1.2 Complex-Geometry Routine

2.1.2.1 Geometric Ordering of Volumes. In order to facilitate the region-search routine, each volume should be contained in one of ten master regions. Further, if geometric complexity warrants, each master region may contain up to ten regions and each region an arbitrary number of subregions. This mode of categorization has the advantage of reducing the number of regions the routine must search at any particular boundary. Also, each master region and each region will have associated with it a base material (which should be either the predominant material therein or that material which would minimize the

geometry description), so that only those volumes containing materials other than the base need be defined.

2.1.2.2 Volumes Acceptable to the Routine. Each volume used to describe the system being studied should be defined by a set of x-planes of one and only one of the following types illustrated in Figure 2-1.

1. Cartesian

   a. Simple. The defined area is a rectangle whose sides are parallel to the y and z axis. The numbers necessary to define the area are: x_p, Y_{min}, Y_{max}, Z_{min}, and Z_{max} (Fig. 2-1a).

      Restrictions: Orientation - $Y_{min} \leq Y_{max}$ and $Z_{min} \leq Z_{max}$.

   b. Complex. The defined area is a quadrilateral. The numbers necessary to define the area are: x_p, Y_1, Z_1, Y_2, Z_2, Y_3, Z_3, Y_4, Z_4 (Fig. 2-1b).

      Restrictions: On the points $P_i = (x_p, Y_i, Z_i)$, $i = 1,2,3,4$

      Orientation: $\overline{P_1P_2}$ and $\overline{P_3P_4}$ are not parallel to the z axis.

      $\overline{P_1P_4}$ and $\overline{P_2P_3}$ are not parallel to the y axis.

      $\min(Z_1Z_2) \leq \min(Z_3Z_4)$, and

      $\min(Y_1Y_4) \leq \min(Y_2Y_3)$.

      Connectivity: P_1 is adjacent to P_2 and P_4

      Convexity: All internal angles less than 180°.

2. Cylindrical

a. Simple. The defined area is a circular annulus. The numbers necessary to define the area are x_p, R_{in}, and R_o (Fig. 2-1c).

b. Complex. The defined area is a sector of a circular annulus. The numbers necessary to define the area are x_p, Θ_1, Θ_2, R_{in}, and R_o (Fig. 2-1d).

c. Complex rectilinear. The defined area is a quadrilateral, two of whose sides are on radii of a circle. The numbers necessary to define the area are:

x_p, Θ_1, Θ_2, R_{in_1}, R_{in_2}, R_{o_1}, and R_{o_2} (Fig. 2-1e).

d. Combination. The defined area is a generalized quadrilateral, two of whose sides are on radii of a circle. The third side is a circular arc, and the fourth, a straight line.

I. The arc forms the inner side. The numbers necessary to define the area are: x_p, Θ_1, Θ_2, R_{in}, R_{o_1}, and R_{o_2} (Fig. 2-1f).

II. The arc forms the outer side. The numbers necessary to define the area are: x_p, Θ_1, Θ_2, R_{in_1}, R_{in_2}, and R_o (Fig. 2-1g).

The defined volumes using these x-planes may be defined in terms of any arbitrary coordinate system. The only restriction is that the x axis of a coordinate system used to define a cylindrical volume must be the axis of the cylinder.

Restrictions: Orientation - All cylinders must be defined to be coaxial with the x axis of the coordinate system used to define the cylinder. All azimuthal angles are positive and measured from the y axis.

$\Theta_1 < \Theta_2$ and $R_{in_i} \leq R_{o_i}$, $i = 1,2$.

All angles are to given in degrees.

2.1.2.3 Method Outline. The segments W_i and the associated material identification numbers M_i are evaluated using a modification of the stepping-point method described above. Flow diagrams of the geometry routine are shown in Figures 2-4 through 2-9.

The general method of evaluating W_i and M_i is as follows:

1. The envelopes for all volumes are computed and the coordinate transformation matrices (to transform a point from the base system to the given system) are computed for all coordinate systems. (Note: since the matrix A represents a rotational transformation, it is orthogonal, i.e., its inverse, A^{-1}, equals its transpose, A^T.) This procedure is shown in Figure 2-4.
2. A detector point is chosen and its coordinates are transformed into Cartesian coordinates and into the base system as shown in Figure 2-5, and all W_i, M_i, and i_{max} are determined for every source point by the method outlined in Steps 3, 4, and 5. At this point, the neutron and/or gamma calculations are made and this step is repeated until the calculations are made for each detector point.
3. A source point is chosen and its coordinates are transformed into Cartesian coordinates and into the base system. Then, the source-detector distance and direction cosines are computed. The stepping point is taken to be the source point (Fig. 2-6).

4. The stepping point is tested against each master region to find the master region in which the stepping point lies (Figs. 2-7 and 2-9). The stepping point is transformed into the coordinate system of the volume and tested against the envelope. If the point is not within the envelope, a new volume is chosen and the procedure begins over. If the point is within the envelope, then the point is tested to see if it is in the volume (Fig. 2-9). If the stepping point is not in the volume, a new volume is chosen and tested. If the stepping point is in the volume, the detector-side boundary of this volume is found by the stepping-point method, and the distance t between this point and the last boundary point is determined (for the first boundary, the source point is used). The volume is then tested to see if it contains subvolumes. If it does not, t is multiplied by the material density associated with the volume and stored as the i^{th} segment W_i; M_i, the material identification number, is also stored. Then, with the stepping point barely beyond the last computed boundary point, this step is repeated. If the volume is found to contain a subvolume (Fig. 2-8), the stepping point is put on the source-side boundary point of the volume, and if the containing volume is a master region, this step is repeated, testing against the regions contained within this master region; or if the containing volume is a region, this step is repeated, testing against the

subregions contained in this region.

5. After the last step has been performed a number of times, one of two things will occur: Upon testing the volumes to find which volume the stepping point is in, it will be found, by elimination, that either the stepping point is in none of the volumes, or, if the set of volumes are master regions, it may be found that the stepping point has gone past the detector point.

   In the first instance (Fig. 2-8), the stepping point is assumed to be in the base material and the portion of the source-detector line lying between the stepping point and the detector-side boundary point of the containing region (or the detector point if the stepping point is outside all master regions) is tested to see if this line passes through a volume (or volumes).

   If it does not, the stepping point is advanced to the detector-side boundary of the containing regions and the distance through the base material is taken to be a segment W_1, and W_1 and the associated M_1 are stored.

   If the volumes of the set being tested are the master regions, i_m is stored, and the program goes to Step 3.

   If the volumes of the set being tested are regions (subregions), then with the stepping point just past the detector-side boundary of the containing volume,

the set of master regions (regions) is considered and the program goes to Step 4.

If a volume (or volumes) lie on this portion of the source-detector line, then the source-side boundary point of the volume closest to the source is found, and the distance that the stepping point goes through the base material is called a segment W_1. W_1 and the associated M_1 are stored. The program then goes back to Step 4.

If the stepping point has gone past the detector, the segment W_1 is taken to be the portion between the volume source-side boundary point and the detector. The program then goes back to Step 3.

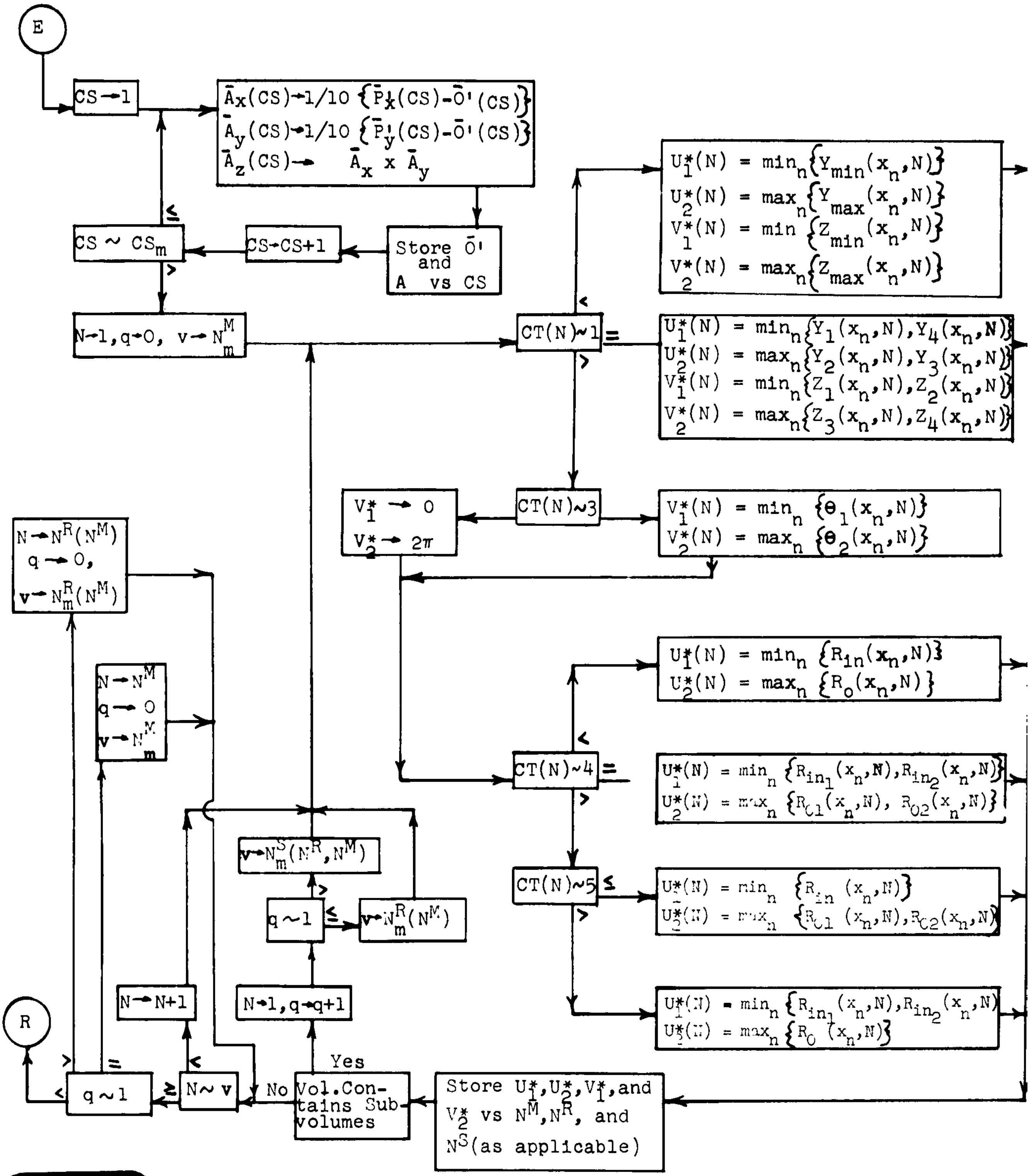
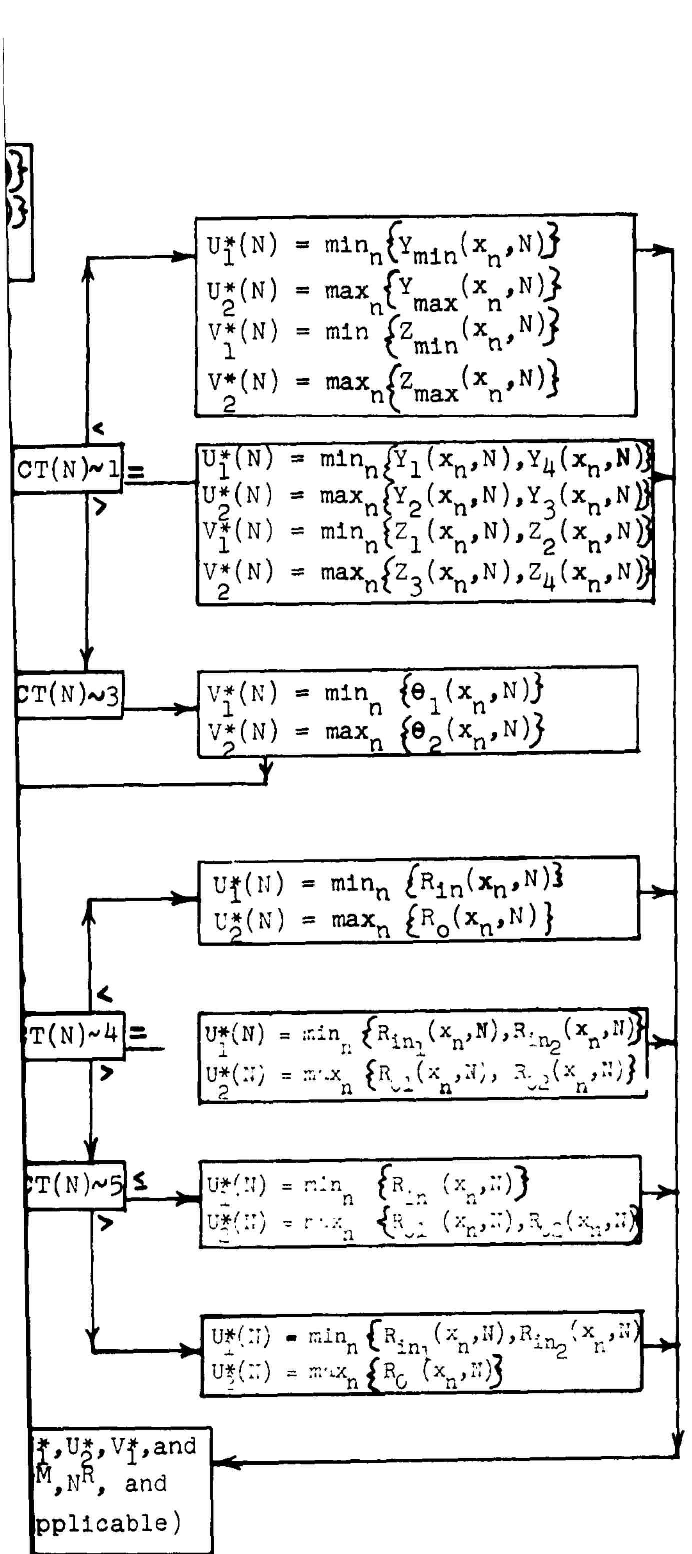


FIGURE 2-4. ENVELOPE PARAMETERS AND COOR TRANSPORTATION ROUTINE

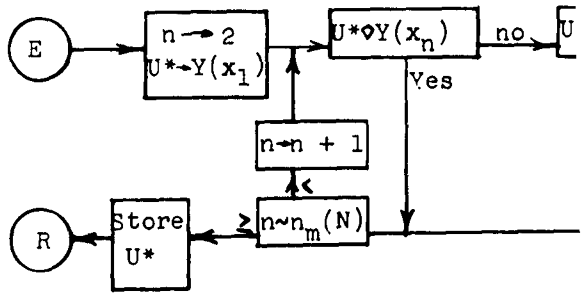


URE 2-4. ENVELOPE PARAMETERS AND COORDINATE TRANSPORTATION ROUTINE

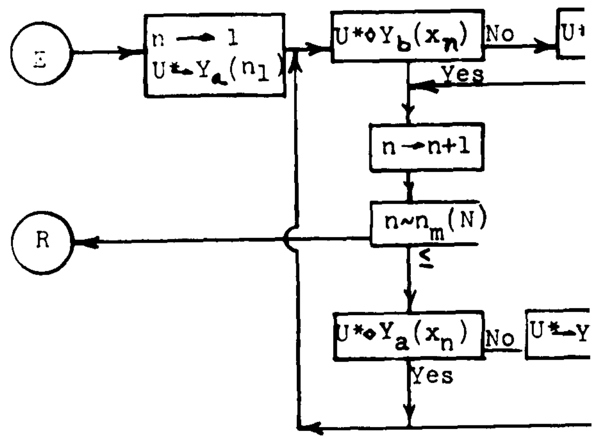
Computation of the U*'s and V*'s.

Note: The symbol ◇ denotes < if the extremum is to be a minimum, and > for a maximum.

1. $U^*(N) = \text{extremum}\ \{Y(x_n,N)\}$:



2. $U^*(N) = \text{extremum}\ Y_a(x_n,N), Y_b(x$



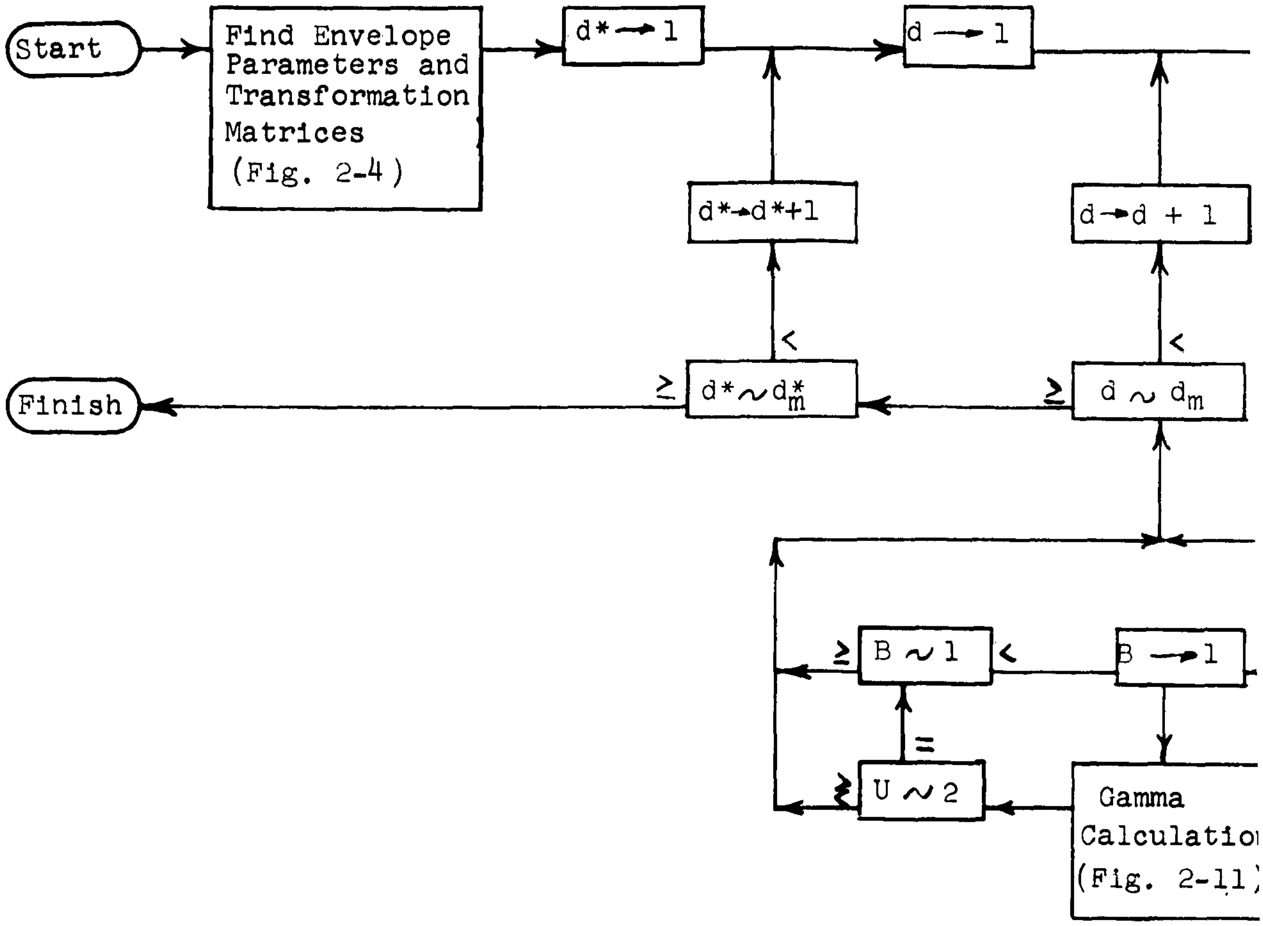
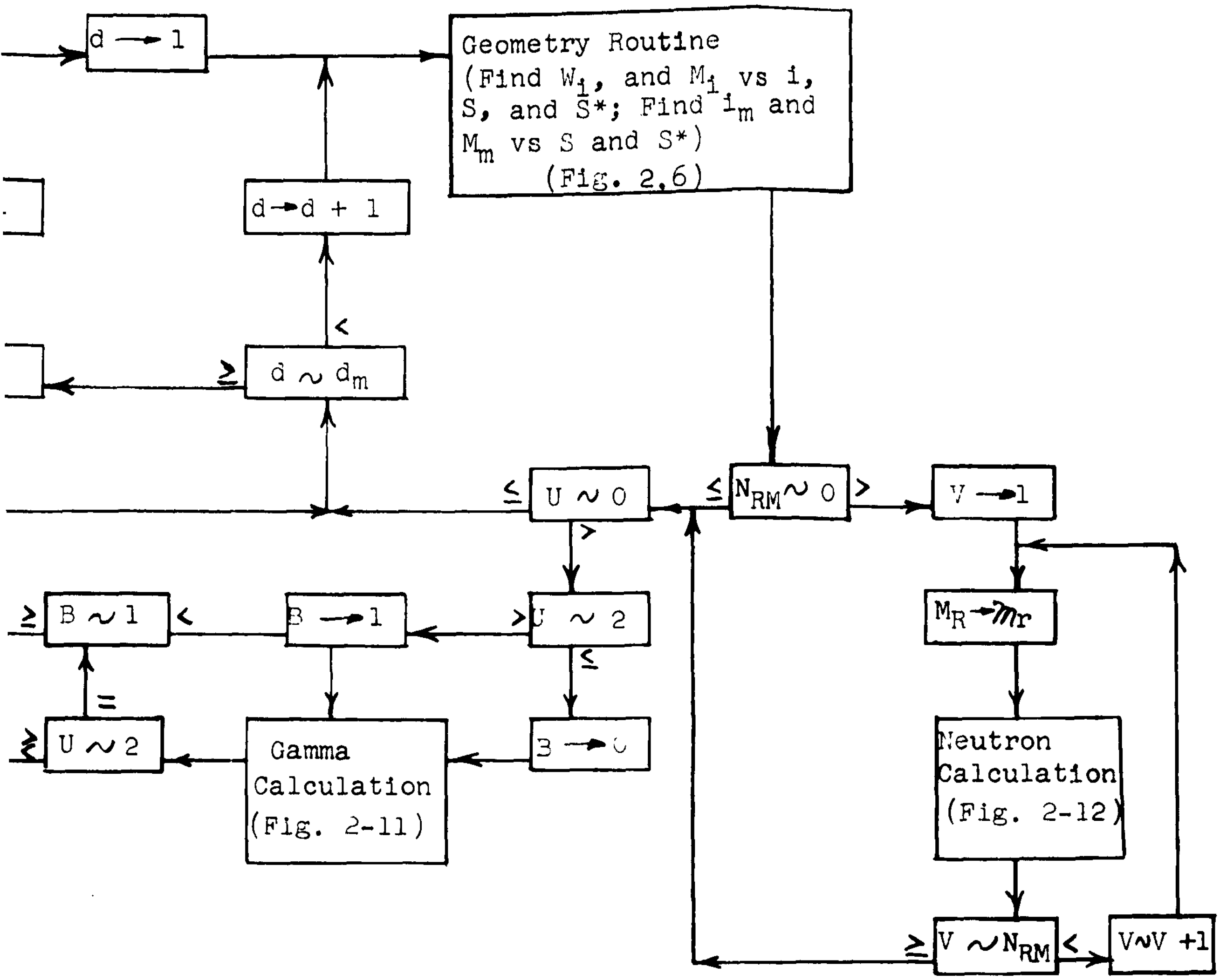


FIGURE 2-5. COMPLEX-GEOMETRY OVERALL



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IPLEX - GEOMETRY OVERALL FLOW DIAGRAM

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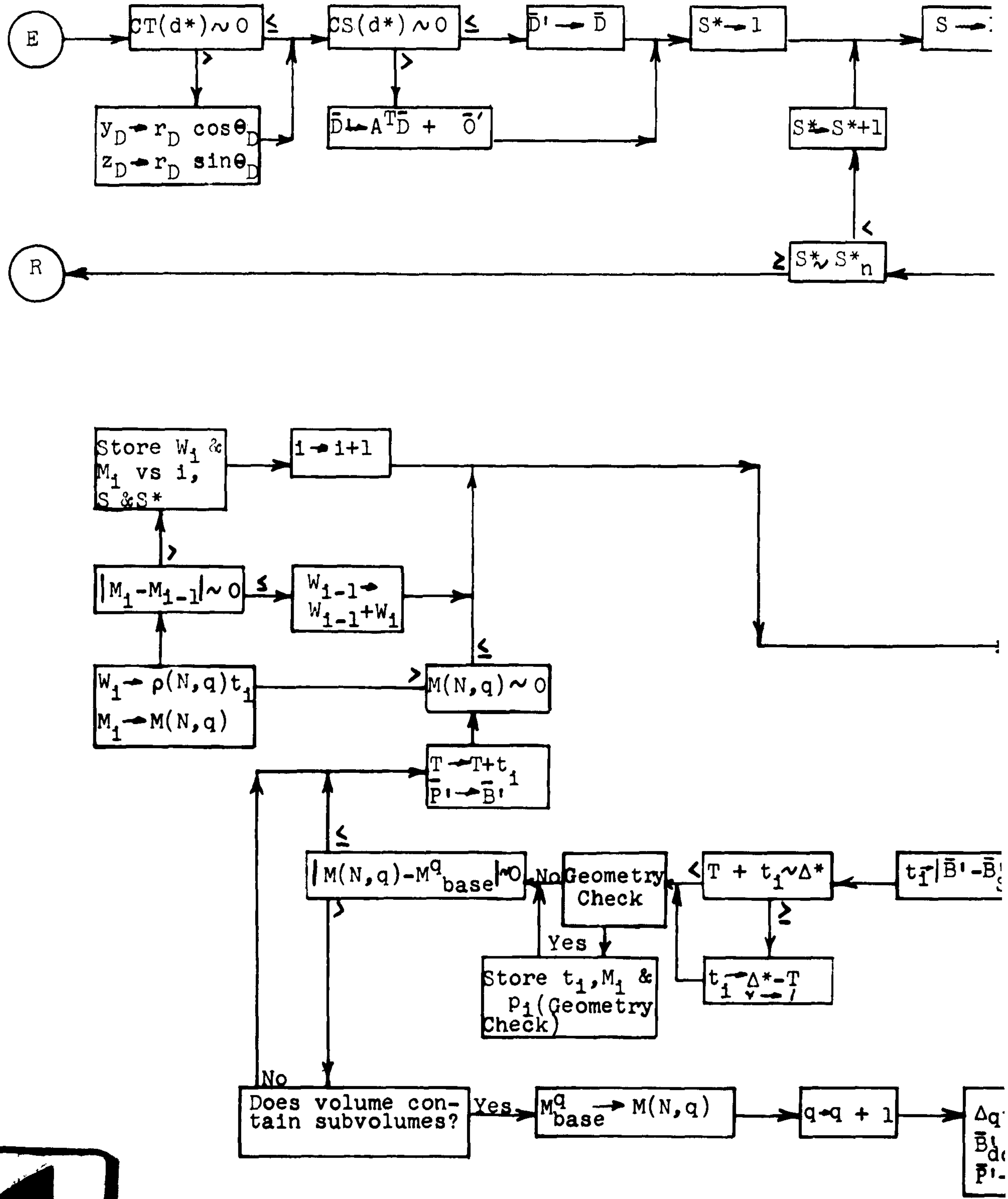

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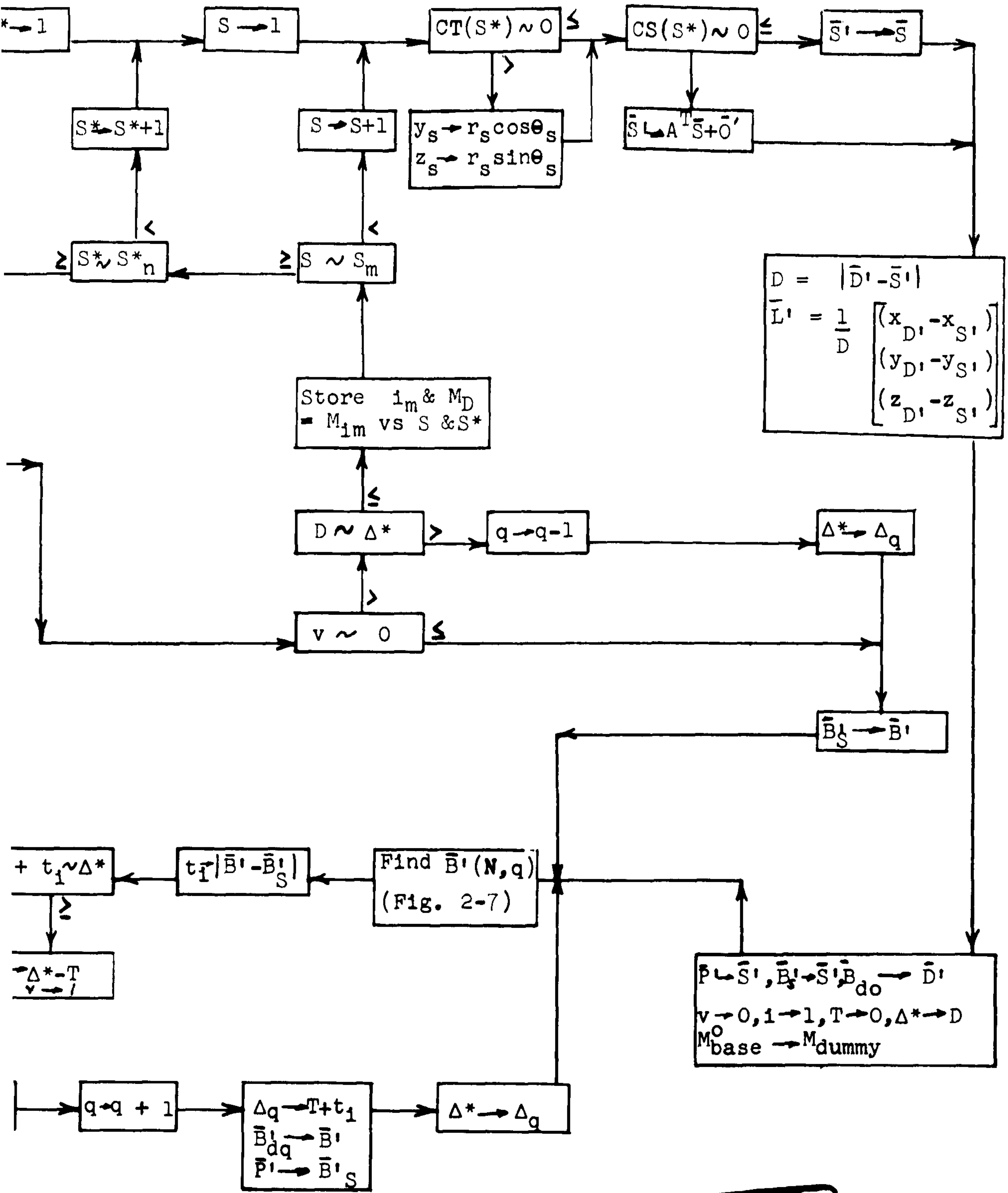
FIGURE 2-6. COMPLEX-GEOMETR



-6. COMPLEX-GEOMETRY ROUTINE

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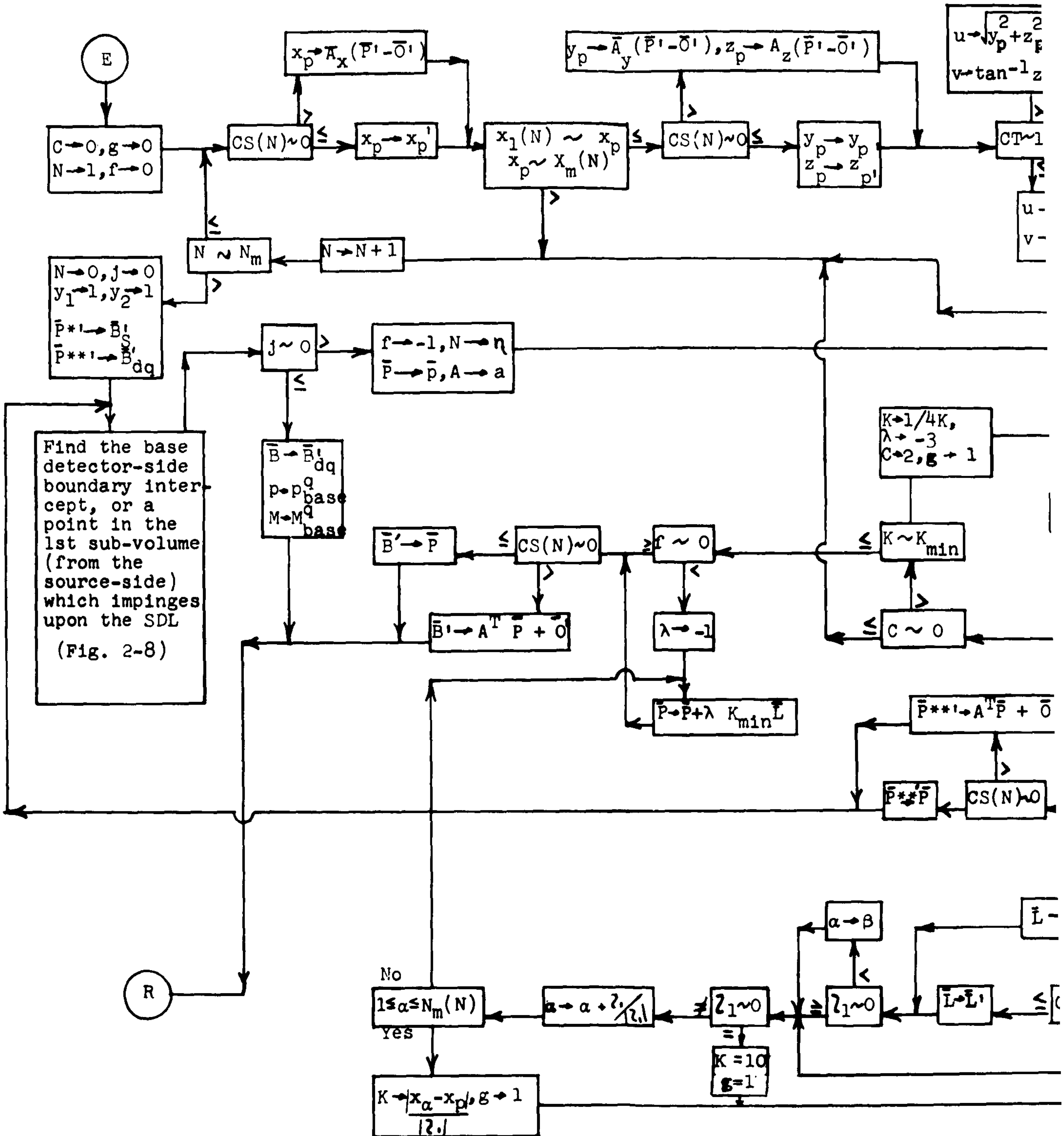
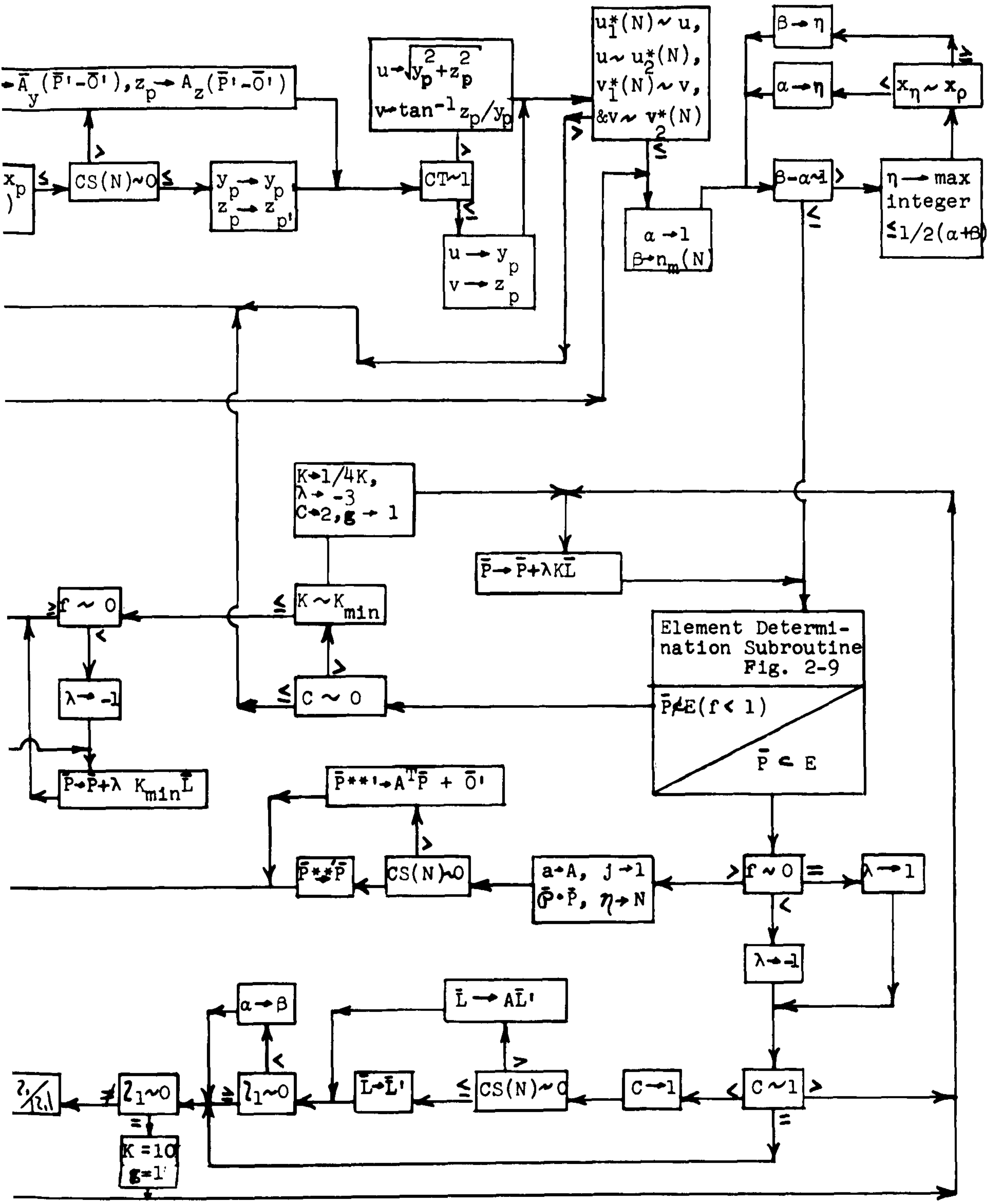


FIGURE 2-7. BOUNDARY DETERMINATION SUBROUTINE



. **BOUNDARY DETERMINATION SUBROUTINE**

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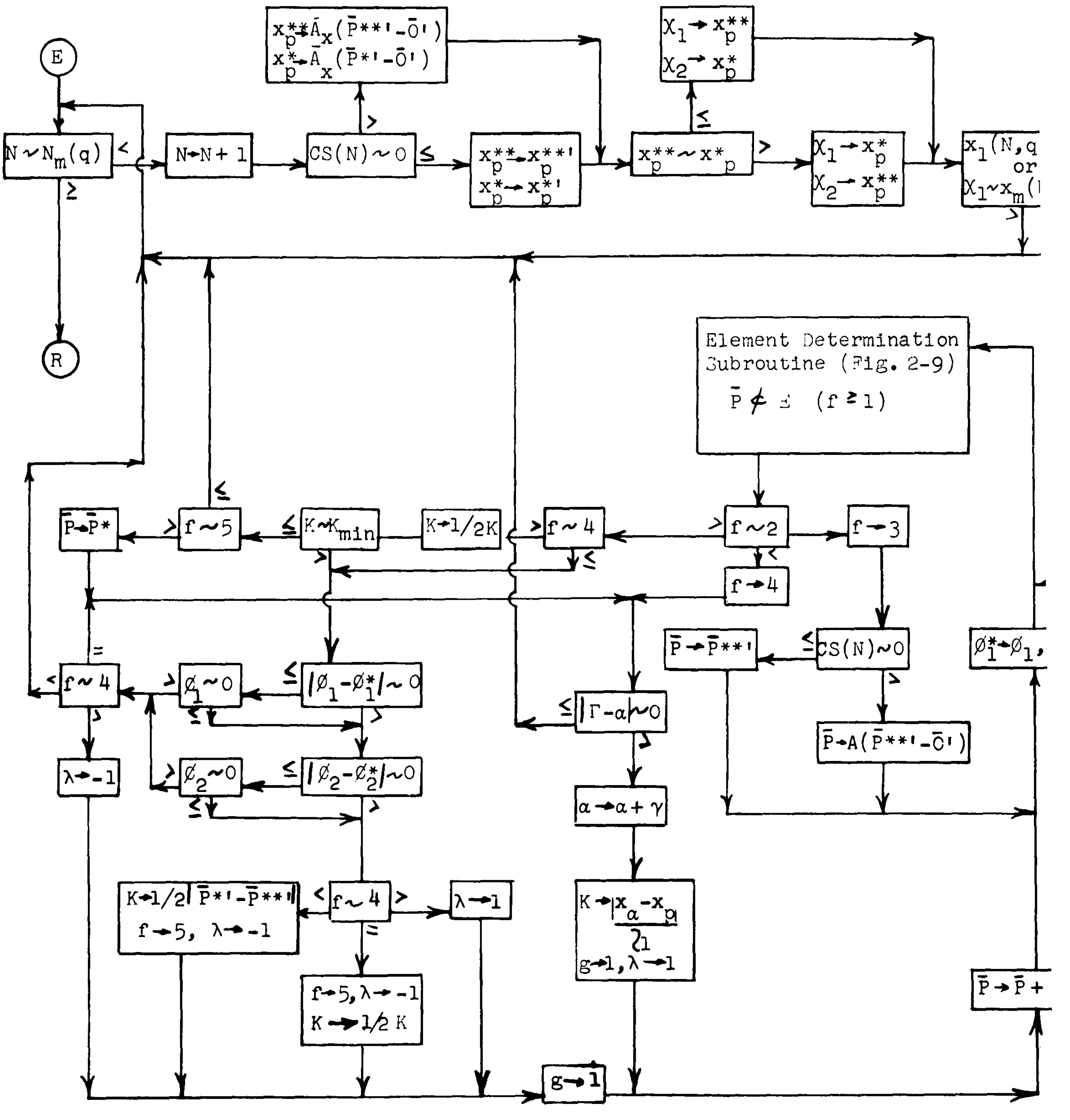
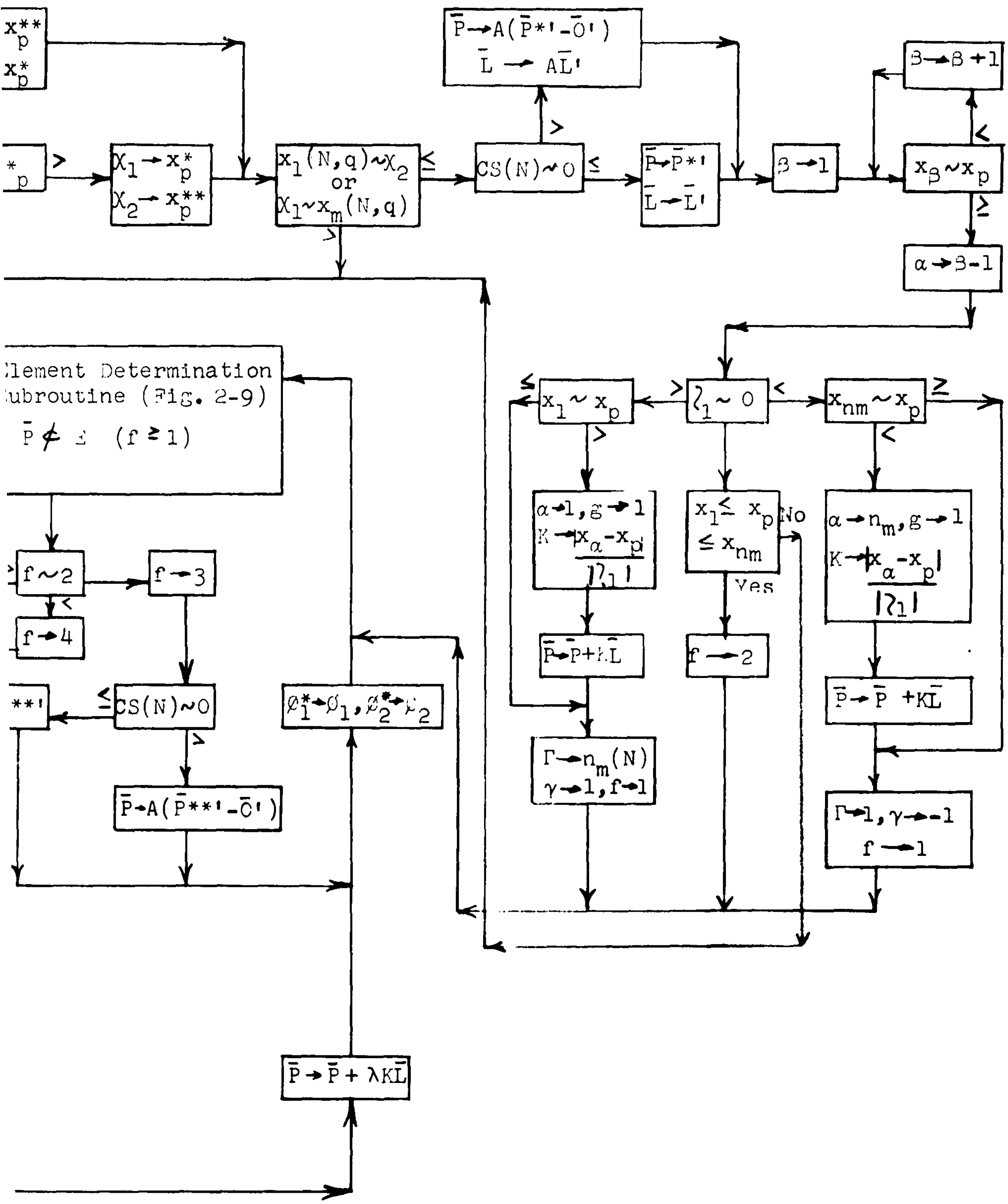


FIGURE 2-8. SUBVOLUME IMPINGEMENT SUB



BVOLUME IMPINGEMENT SUBROUTINE

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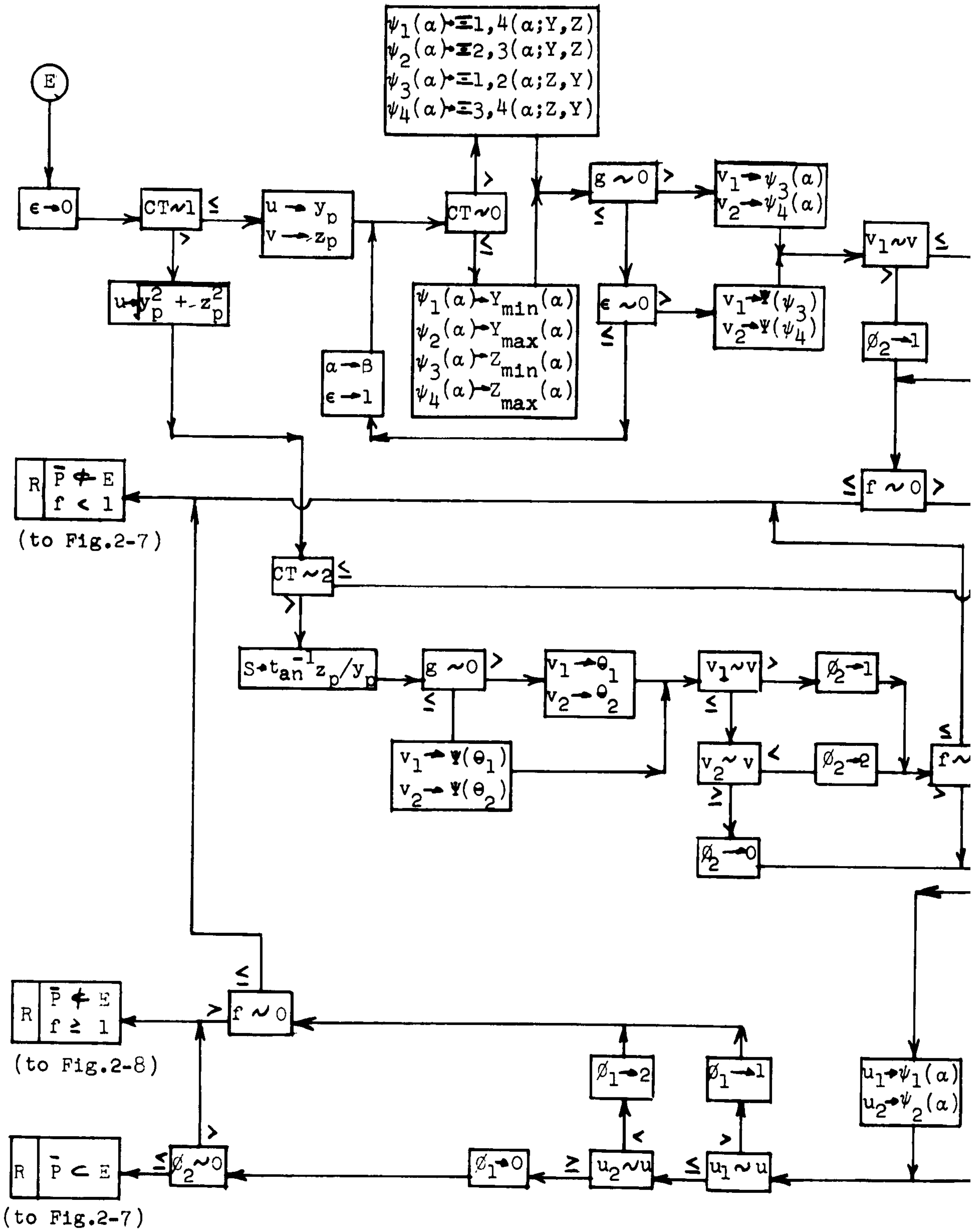
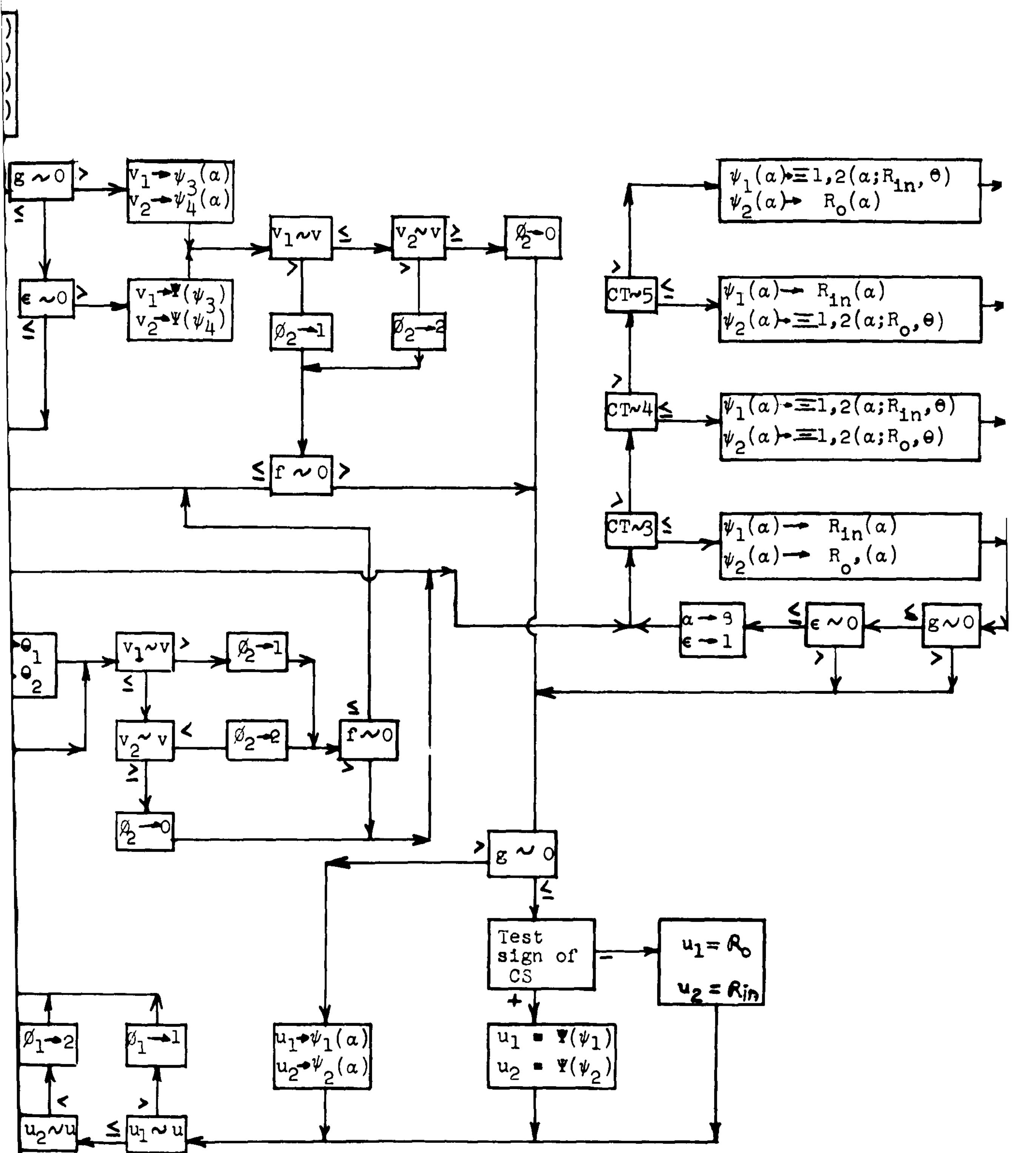


FIGURE 2-9. ELEMENT DETERMINATION



E 2-9. ELEMENT DETERMINATION SUBROUTINE

2.2 Calculation of the Gamma-Ray Number-Flux Energy Spectrum, Dose Rate, and Heat Generation Rate

The gamma-ray number-flux energy spectrum at a point in space may be divided into two components, a direct-beam portion and a scattered portion. Thus, $F(E_a)$, the spectral point for energy E_a at a point isotropic detector located at a point r in an infinite medium due to photons emitted from a point isotropic source located at the origin, and with source spectrum $S(E_b)$, is given by

$$F(E_a) = \frac{S(E_a)\, e^{-\mu(E_a)r}}{4\pi r^2} + \int_{E_a}^{\infty} S(E_b)\, I'(E_b,E_a,r)\, dE_b, \qquad (1)$$

where the first term on the right-hand side of the equation represents the direct-beam component, and $\mu(E_a)$ is the linear attenuation coefficient for photons with energy E_a in the material in question. The second term in Equation 1 represents the scattered portion of the spectrum; the function $I'(E_b,E_a,r)$ is the scattered portion of the differential number spectra of the photon number flux in an infinite medium. The integration in the second term is over all initial photon energies greater than or equal to E_a.

The differential energy spectra of the gamma-ray number flux at a point isotropic detector resulting from a point isotropic source, in an infinite medium, as computed by the moments method (Ref. 2), have been used in determining the function $I'(E_b,E_a,r)$. These differential energy spectra I_o may be defined as probabilities, per unit initial photon energy, that a quantum

of the gamma-ray energy flux will be degraded from an initial energy E_b to an energy E_a ($E_a \leq E_b$) by the time the quantum reaches a point isotropic detector at r. Hence, the differential energy spectra and the differential number spectra are related by

$$\frac{I_o(E_b, E_a, r)}{E_a} = I'(E_b, E_a, r). \tag{2}$$

The data tabulated in Reference 2 are in the form

$$f = 4\pi r^2 \; e^{\mu(E_b) r} \, I_o(E_b, E_a, \mu(E_b) r) \tag{3}$$

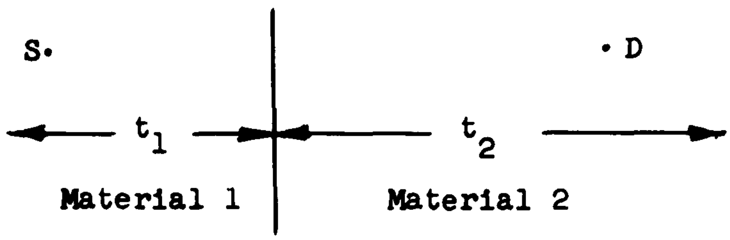
for discrete values of the three variables and for various materials. Thus, when the integral is approximated by a finite sum, the equation to be solved, from Equations 1 and 2 and the definition above (Eq. 3), is

$$F(E_a) = \frac{S(E_a)\, e^{-\mu(E_a) r}}{4\pi r^2} + \sum \frac{S(E_b)\, f\, e^{-\mu(E_b) r}}{4\pi r^2 \, E_a} \, hf(E_a, E_b), \tag{4}$$

where $hf(E_a, E_b)$ is a numerical integrating, or histogram, factor, and the summation is over initial photon energy E_b, and is from the energy E_a to the maximum value of initial photon energy.

Equation 4 defines the energy spectrum of the gamma-ray number flux in an infinite medium in terms of the spectrum at a point detector at a distance r from the point isotropic source.

In order to apply this method to determining spectra in and around reactor shield systems, it is necessary to assume that the spectra may be reconstituted at each boundary, and that the spectrum on the detector side of a boundary is equal to the spectrum on the source side of the boundary.[1] As an example of this idea, consider a source and detector shown in the sketch.



Photons from the source S, whose spectrum is taken to be $S_1(E_b)$, penetrate the two slabs with thicknesses t_1 and t_2 and are detected at the receiver at D. The spectrum at D, as an application of Equation 4, is given by:

$$F(E_a) = \frac{1}{4\pi D^2}\left\{S_2(E_a)\, e^{-\mu_2(E_a)t_2} + \sum \frac{S_2(E_b) f\, e^{-\mu_2(E_b)t_2}}{E_a}\, hf(E_a,E_b)\right\},$$

where D is the source-detector distance, and

S_2 is the spectrum (excluding geometric attenuation) at the boundary between the two materials.

S_2 is given in terms of S_1, the source spectrum, by

$$S_2(E_a) = S_1(E_a)\, e^{-\mu_1(E_a)t_1} + \sum \frac{S_1(E_b)\, f\, e^{-\mu_1(E_b)t_1}}{E_a}\, hf(E_a,E_b).$$

---

1 The validity of this assumption, and the second assumption that follows, has been tested experimentally; the experiment and analysis are reported in References 5 and 6.

A second assumption inherent in this method is that differential energy spectra for infinite media may be used to describe radiation transport in finite media. One way of estimating the importance of this finiteness of geometry, is to assume the correction to be independent of final energy and to multiply the differential energy spectra by the edge correction factors of Berger and Doggett (Ref. 7).

These factors are defined as

$$g = \frac{\int_0^{E_b} \left\{ I_0^r \; (E_b, E_a, r)/E_a \right\} dE_a}{\int_0^{E_b} \left\{ I_0^\infty \; (E_b, E_a, r)/E_a \right\} dE_a} \; , \tag{5}$$

where $I_0^r(E_b, E_a, r)$ and $I_0^\infty(E_b, E_a, r)$ are differential energy spectra for a finite slab and for an infinite medium, respectively. The function g may be rewritten as

$$g = \frac{\int_0^{E_b} \frac{I_0^r}{I_0^\infty} \cdot \frac{I_0^\infty}{E_a} \quad dE_a}{\int_0^{E_b} \frac{I_0^\infty}{E_a} \; dE_a} \; .$$

It is assumed that the ratio I_0^r/I_0^∞ is independent of degraded energy E_a and, hence, that the edge corrections are just the ratio of the differential energy spectra for a finite medium and the spectra for an infinite medium:

$$g = \frac{I_0^r(E_b, E_a, r)}{I_0^\infty(E_b, E_a, r)} \; .$$

Thus, if edge corrections are to be used, the function f in Equation 4 should be replaced by fg. This correction is optional in the codes.

It has been assumed that any source may be replaced by a set of point isotropic sources; hence, the spectrum from the total source is taken to be the sum, over all source points, of the spectra due to each point. The points of this total spectrum are then multiplied by either the flux-to-dose or flux-to-heat conversion factors and by the appropriate integrating or histogram factors, and summed, over energy, to give either dose rate or heat generation rate.

2.2.1 Spectral Calculation (for one source point)

The method used to evaluate the spectral equation (Eq. 4) is shown in Figure 2-10. This flow diagram shows the method for obtaining the spectrum at a detector from one source point, using the segments determined by the geometry routine.

The evaluation of the spectral points F_a^{γ} is as follows:

1. The spectrum S_b associated with the source point[1] (from Library 3) is taken to be the working spectrum S_b^{γ}, and the first segment W_1 and the material number M_1 for this segment are set up to be used. Note: the subscript 1, on W and M is used to denote segment number.
2. The subscript a, which denotes final energy (and, in a manner similar to b, increases as final energy decreases),

[1] The subscript b denotes initial energy, and b increases as initial energy decreases; i.e., b = 1 denotes 10 Mev, b = 2 denotes 9 Mev, etc.

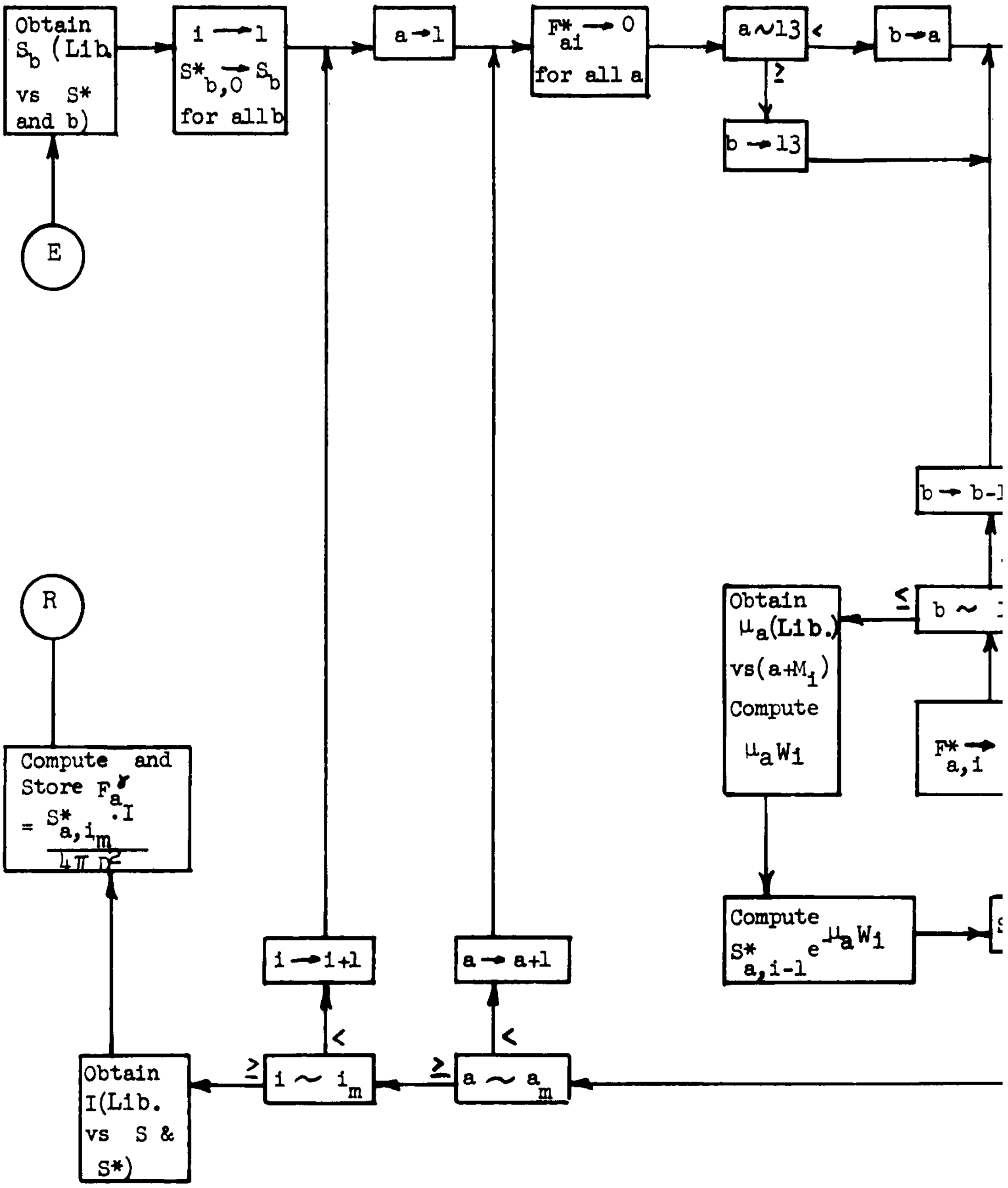
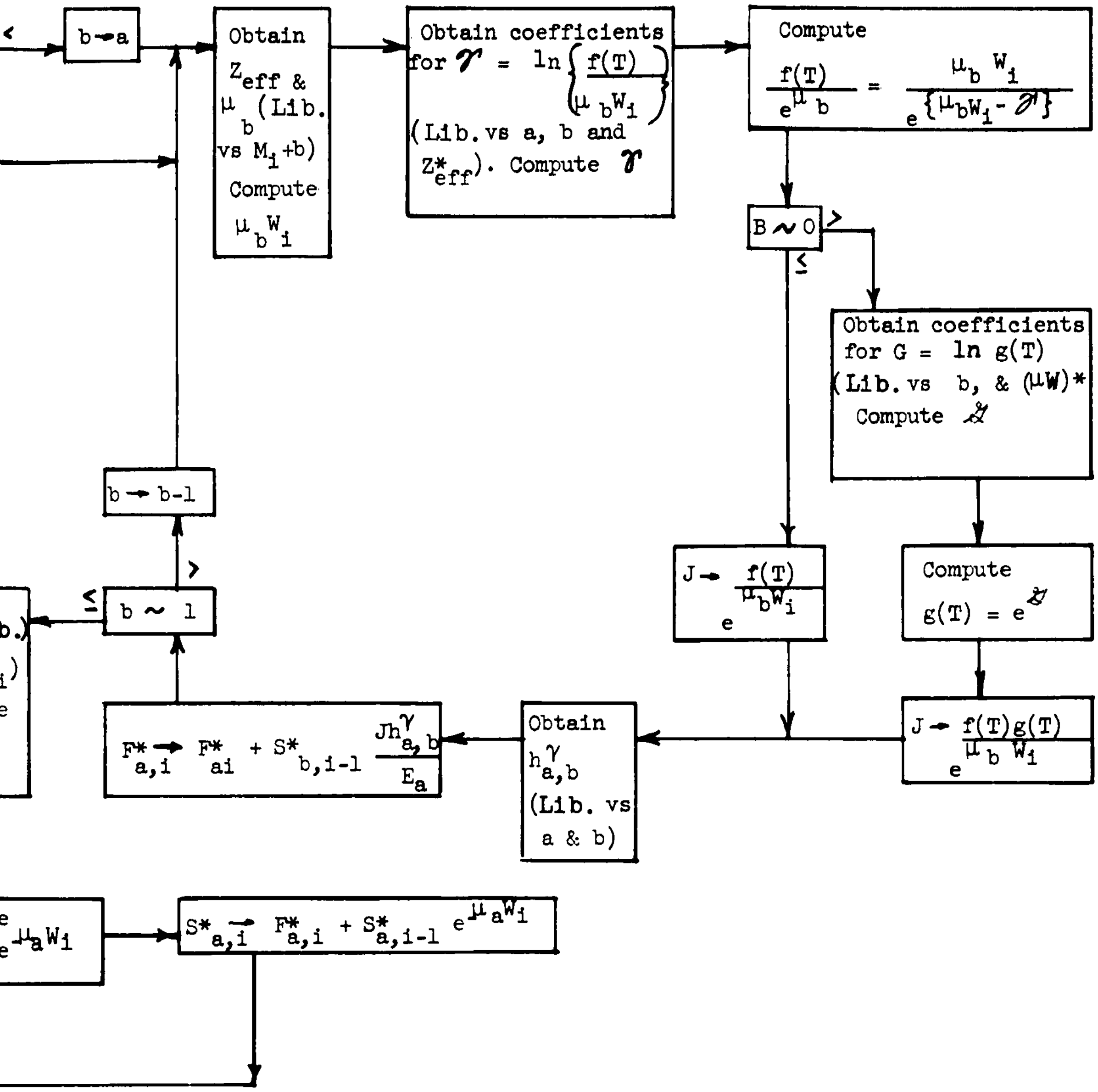


FIGURE 2-10. GAMMA SPE



b → a
Obtain Z_{eff} & μ_b (Lib. vs M_i+b) Compute $\mu_b W_i$
Obtain coefficients for $\mathcal{T} = \ln\left\{\frac{f(T)}{\mu_b W_i}\right\}$ (Lib. vs a, b and Z^*_{eff}). Compute $\mathcal{T}$
Compute $\frac{f(T)}{e^{\mu_b}} = \frac{\mu_b W_i}{e^{\{\mu_b W_i - \mathcal{T}\}}}$
B ~ 0
Obtain coefficients for G = ln g(T) (Lib. vs b, & (μW)* Compute $\mathcal{G}$
b → b-1
b ~ 1
$J \rightarrow \frac{f(T)}{e^{\mu_b W_i}}$
Compute $g(T) = e^{\mathcal{G}}$
$J \rightarrow \frac{f(T)g(T)}{e^{\mu_b W_i}}$
Obtain $h^{\gamma}_{a,b}$ (Lib. vs a & b)
$F^*_{a,i} \rightarrow F^*_{ai} + S^*_{b,i-1} \frac{Jh^{\gamma}_{a,b}}{E_a}$
$S^*_{a,i} \rightarrow F^*_{a,i} + S^*_{a,i-1}\, e^{\mu_a W_i}$

2

is set equal to one. F_a^*, the scattered term of the spectrum is set equal to zero in order to initialize the summation over initial energy (Eq. 4).

3. The value of a is tested. If a is less than 13, b is set equal to a, if a is greater than or equal to 13, b is set equal to 13.

4. The values for the mass attenuation coefficient, μ, and effective atomic number, Z_{eff}, are taken from Library 1 for b and M_i. W_i comes from the geometry routine, and the number of relaxation lengths of material penetrated, $\mu_b W_i$, is calculated. The coefficients for the differential energy spectral function[1]

$$\gamma = \ln\left\{\frac{f}{\mu_b W_i}\right\}$$

are found (from Library 2) as a function of a and b, and the function $fe^{-\mu_b W_i}$ is evaluated using the variables Z_{eff} and $\mu_b W_i$.

5. The parameter B is tested to see if edge corrections are required for this calculation. If B is greater than zero, the coefficients for the edge corrections[2]

---

[1] The differential energy spectra have been fitted to a quadratic in $\mu_b W$ and Z_{eff} for each possible combination of a and b (since degraded energy, for a particular case, must be less than or, at most, equal to the initial energy, $a \geq b$). This representation has the form

$$\gamma = \ln\left\{\frac{f}{\mu_b W}\right\} = A_1(\mu_b W)^2 + A_2(\mu_b W) + A_3(\mu_b W)Z_{eff} + A_4 Z_{eff} + A_5 Z_{eff}^2 + A_6$$

It has been found necessary to section the curve fits in Z_{eff} into three ranges (0-26, 26-74, and 74-92) and to use different sets of coefficients for each range. See Reference 3.

[2] The edge corrections have been fitted to a quadratic of the form

$$\delta = \ln g = B_1(\mu_b W)^2 + B_2(\mu_b W) + B_3(\mu_b W)Z_{eff} + B_4 Z_{eff} + B_5 Z_{eff}^2 + B_6$$

for each value of b. It has been found necessary to section the curve fits in $\mu_b W$ into two ranges (0-4 and 4-20) and to use different coefficients for each range.

are found (from Library 2) as a function of b, and the function g is evaluated using the coefficients Z_{eff} and $\mu_b W_i$. Then,

$$J = f \cdot g e^{-\mu_b W_i} = \mu_b W_i e^{+[\gamma + \mathcal{Y} - \mu_b W_i]}$$

is formed. If B is less than or equal to zero, J is given by

$$J = f e^{-\mu_b W_i}$$

6. The histogram factor $hf_{a,b}$ and final energy E_a are found (from Library 2) and

$$F_a^* \rightarrow F_a^* + S_{b,i-1}^* \; J \frac{hf_{a,b}}{E_a} \qquad (6)$$

is formed, where $S_{b,i-1}$ is the current value of the spectral point for b. Expression 6 has the form of the summation of Equation 4, except that the limits on the summation are from E_a to the current value of E_b.

7. The parameter b is tested, and if b is greater than one, the current value of b is decremented by one and the routine goes to Step 4. If the current value of b is one, F_a^* is now the scattered term of Equation 4 and the direct-beam term is to be computed next. First, the mass attenuation coefficient μ is found (from Library 1) for a and M_i. Then $\mu_a W_i$ is computed and the new current value of the spectral point for a, $S_{a,i}^*$, is given by

$$S_{ai}^* = F_a^* + S_{a,i-1} e^{-\mu_a W_i}$$

Next, a is tested and if a is less than 14, a is incremented by one, and the routine goes to Step 3. If a is equal to 14, i is tested, and if i is less than i_{max} (which is computed by the geometry routine), i is incremented by one, and the routine goes to Step 2; if i is equal to i_{max}, the function F_a^{γ} is computed from

$$F_a^{\gamma} = \frac{S^*_{a,i\,max} \cdot I}{4\pi D^2}, \qquad (7)$$

where I is the source intensity (from Library 3),

D is the source-detector distance (from the geometry routine), and

S^*_a, i_{max} is the new current value of the spectral point for a and for the last, or $i_{max}{}^{th}$, segment.

The function F_a^{γ} is computed for each value of a, and is the evaluation of the photon number-flux spectrum at the detector due to the given source point.

2.2.2 Determination of the Spectrum, Dose Rate, and Heat Generation Rate

The method used to determine the spectrum, dose rate, and heat generation rate is shown in Figure 2-11. This flow diagram shows the method for obtaining these parameters from the spectra determined by the spectral routine (Sec. 2.2.1).

The method is as follows:

1. The following parameters are set to zero in order to initialize the various summations: $D^{\gamma*}$, $H^{\gamma*}$, and $G_a^{\gamma*}$ — the dose rate, heat generation rate, and spectrum,

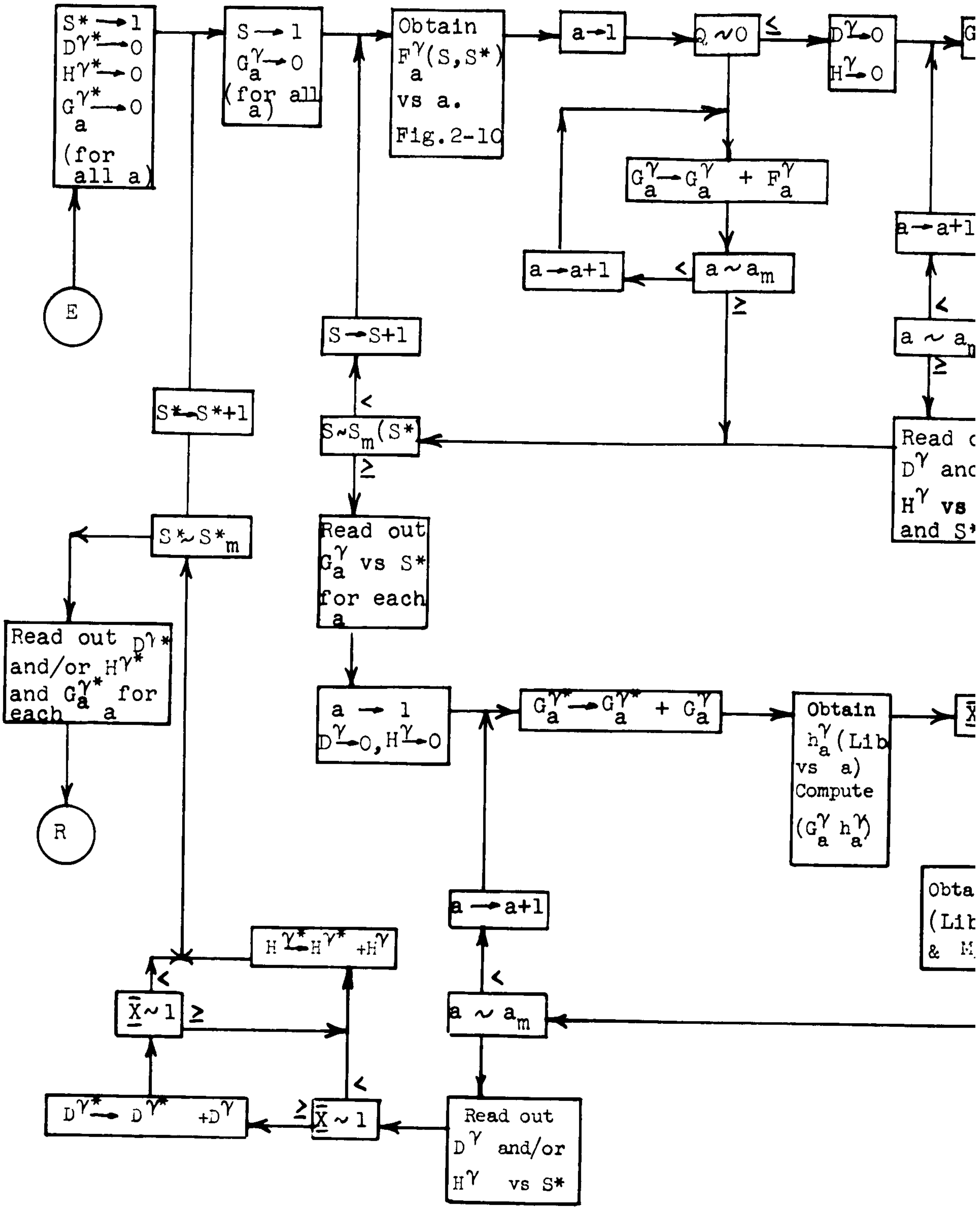


FIGURE 2-11. GAMMA I

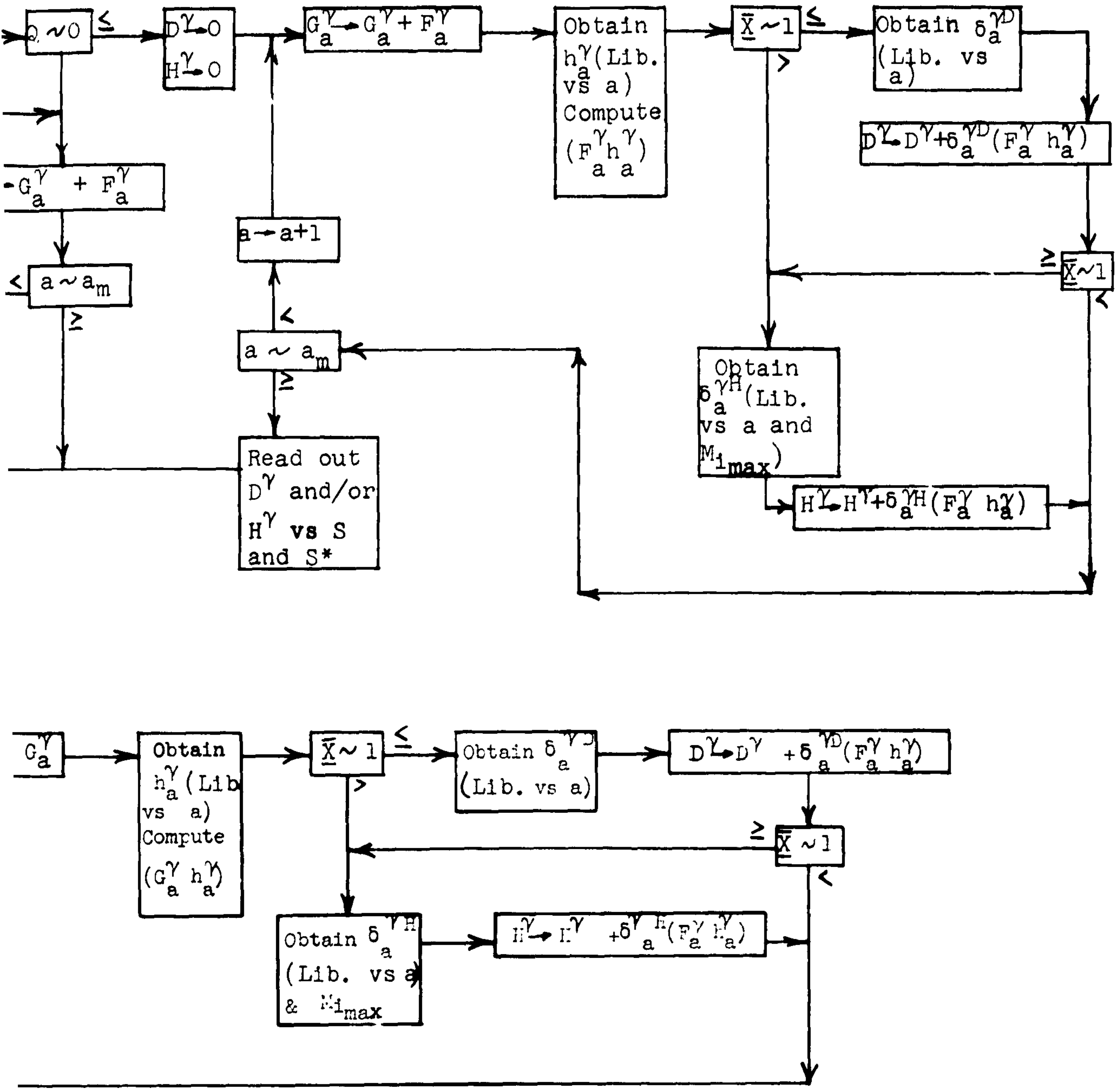


FIGURE 2-11. GAMMA ROUTINE

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respectively—summed over all source groups. The source group index S* is set to one.

2. The spectrum G_a^γ, summed over all source points in source group S*, is set to zero in order to initialize the summation over source points. The source-point index S is set to one.

3. The spectral function F_a^γ for source-point S of source-group S* is found (Sec. 2.2.1).

4. The degraded-energy index a is set to one; then Q, the source-point print option is tested. If Q is one, dose rates and/or heating rates due to each source point will be calculated to be printed out in addition to the normal printout. If Q is two, only the normal printout will be made, and for each value of a, F_a^γ obtained in Step 3 will be added to the current value of G_a^γ. If Q is one, the dose rate due to each source point will be calculated if $X \leq 2$ and the heat generation rate will be calculated if $X \geq 2$. In addition, for each value of a, F_a^γ, obtained in Step 3, will be added to the current value of G_a^γ. The equations used to compute the dose rates and heat generation rates are:

$$\mathcal{D}^\gamma = \sum_{a=1}^{14} F_a^\gamma \, \delta_a^{\gamma D} \, hf_a \quad \text{and} \quad H^\gamma = \sum_{a=1}^{14} F_a^\gamma \, \delta^{\gamma H} \rho \, hf_a ,$$

where hf_a are integrating or histogram factors from Library 2,

$\delta_a^{\gamma D}$ are flux-to-dose conversion factors from Library 2,

$\delta_a^{\gamma H}$ are flux-to-heat conversion factors for material of unit density, and are a function of $M_{1_{max}}$ (from the geometry routine) as well as a; they are listed in Library 1, and

ρ is the material density associated with $M_{1_{max}}$ from the problem deck.

5. S, the source point index, is tested; if S is less than S_{ms*}, the total number of source points in the S^{*th} source group, S is incremented by one and the routine goes to Step 3. If S is greater than or equal to S_{ms*}, G_a^γ is now the total spectrum for group S^* and the dose rates and/or heat generation rate are calculated as in Step 4 with G_a^γ substituted for F_a^γ. If $X \leq 2$, $D^{\gamma *}$ is replaced by the sum of the current value of $D^{\gamma *}$ and D^γ the dose rate due to the S^{*th} source group. If $X \geq 2$, $H^{\gamma *}$ is replaced by the sum of the current value of $H^{\gamma *}$ and H^γ the heat generation rates due to the S^{*th} source group. In any case, $G_a^{\gamma *}$ is replaced by the sum of the current value of $G^{\gamma *}$ and G^γ in order to generate the total spectrum. S^* is then tested, and if S^* is less than S^*_m, the total number of source groups, S^* is incremented by one and the routine goes to Step 2. If S^* is greater than or equal to S^*_m, then the current values of $G_a^{\gamma *}$, $D^{\gamma *}$, and $H^{\gamma *}$ are the total spectrum, dose rate, and heat generation rate, respectively, at a detector due to all source points.

The data generated by this routine for program output are:

a. G_a^{γ} and $G_a^{\gamma *}$ (for a = 1 through 14) - the spectra of the gamma-ray number flux summed over each source group and over all source groups, respectively.

b. D^{γ} and $D^{\gamma *}$ - these are generated only if $X \leq 2$; they are, respectively, the dose rate due to each source group, and the total dose rate. If Q is one, in addition to the above, the dose rate due to each source point is printed out.

c. H^{γ} and $H^{\gamma *}$ - these are generated only if $X \geq 2$; they are, respectively, the heat generation due to each source group, and the total heat generation rate. If Q is one, in addition to the above, the heat generation rate due to each source point is printed out.

2.3 Calculation of the Neutron Number-Flux Energy Spectrum, Dose Rate, and Heat Generation Rate

The neutron calculation is based on the assumption that the moments-method dose rates and energy spectra of the fast-neutron number flux due to a point isotropic Watt fission source in an infinite medium of a few selected reference materials may be used to determine the spectra and dose rates in arbitrary combinations of arbitrary materials.

The method used to determine these fluxes and dose rates is based upon the concept of an equivalent segment W_{eq}. The equivalent segment for a material whose actual segment is W and whose removal cross section (per unit density) is Σ_R is given by

$$W_{eq} = \frac{\Sigma_R}{\Sigma_{RR}} W , \tag{1}$$

where Σ_{RR} is the removal cross section (per unit density) for the chosen reference material. The total equivalent segment is the sum of the equivalent segments for each segment along the source-detector line. This total equivalent segment is used to determine the attenuation factors for the spectral points and dose rates, and these factors, when multiplied by the source intensity, and the geometric attenuation factor are taken to be the values of the spectral points and dose rate at the chosen detector due to one source point. Hence, the spectral points and dose rate at the detector due to the total source is the sum, over all source points, of the spectral-point or dose-rate function per source point. The heat generation rate is computed from the total

spectral function by multiplying it by appropriate integrating or histogram factors and the fast-neutron flux-to-heat conversion factors (Appendix B) and summing over neutron energy. A comparison of the various reference materials in a given geometry is located in Appendix C.

The method used to perform the neutron calculations is shown in Figure 2-12. This flow diagram shows the method for obtaining these parameters from moments-method data for neutrons.

The method used is as follows:

1. The following parameters are set to zero in order to initialize the various summations: D_a^{n*} (for a = 1 to a_{max+1}) - the first a_{max} of these are the neutron spectral terms, and the a_{max+1} term is the dose-rate function summed over source points; a is the neutron-energy index and increases with decreasing energy, i.e., a = 1 for E_{max}; H^{n*} - the neutron heat generation rate summed over all source points. S*, the source-group index, is set to one.
2. The following parameters are set to zero in order to initialize the various summations: D_a^n (for a = 1 to a_{max+1}) the neutron spectral terms and dose rate and H^n, the heat generation rate summed over all source points in source groups S*. S, the source point index is set to one.
3. The total equivalent segment for source point S of source group S* is found from

$$W_{eq} = \frac{1}{\Sigma_{RR}} \cdot \sum_{i=1}^{i_{max}} \Sigma_{R_i} \quad W_i \quad ,$$

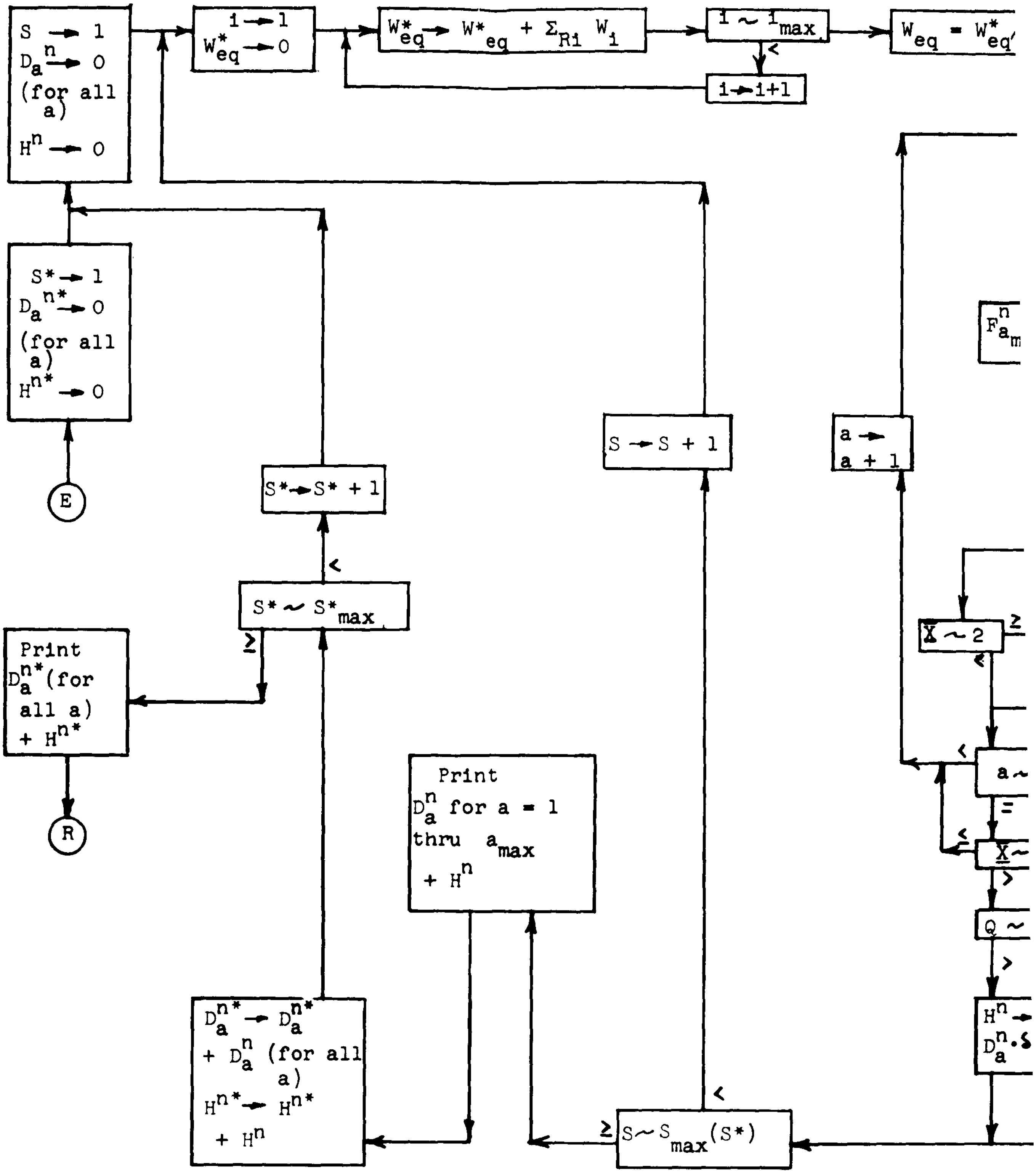


FIGURE 2-12. NEUTRON ROUTINE

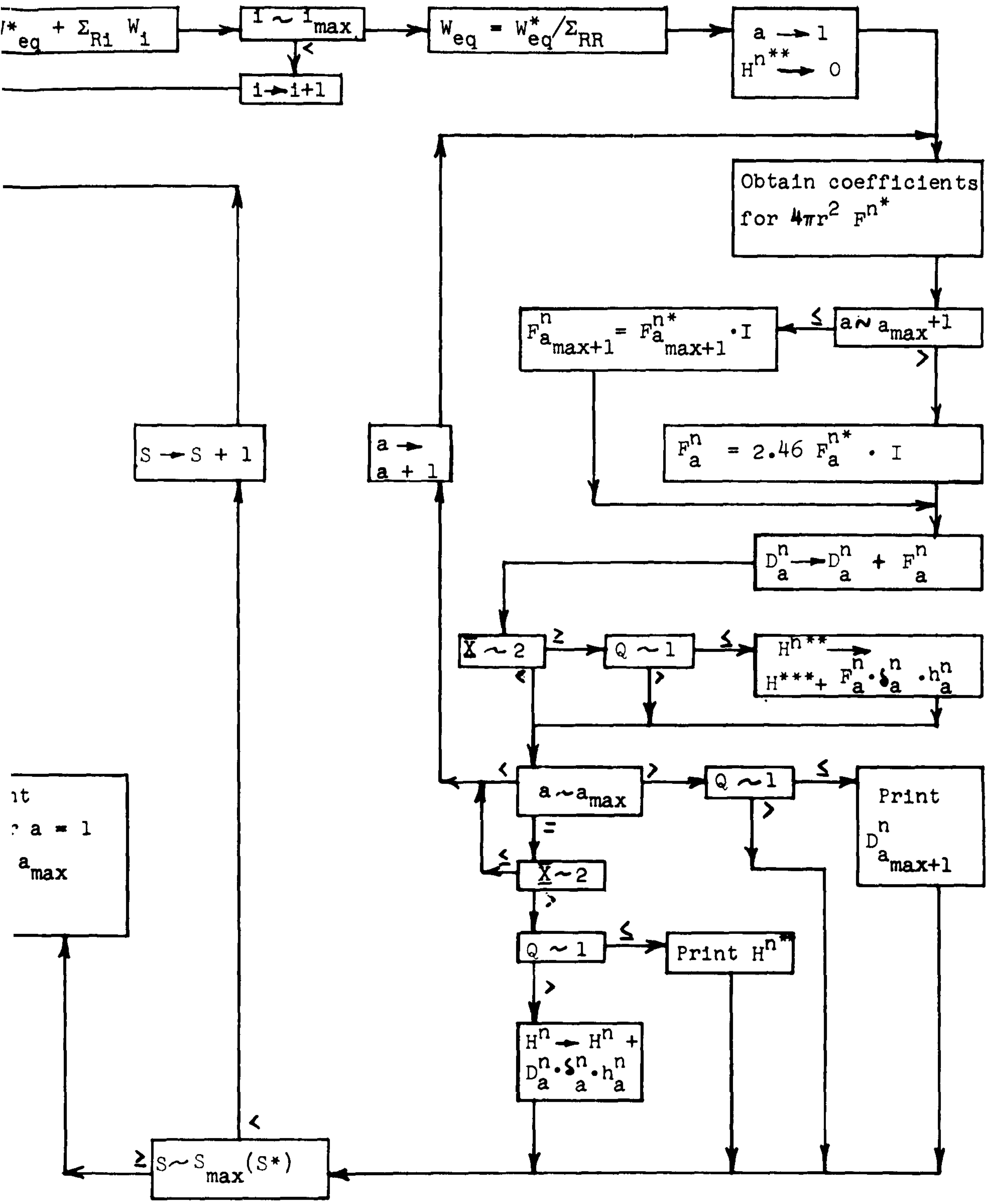


FIGURE 2-12. NEUTRON ROUTINE

2

where i_{max} is the number of segments on the source-detector line (from the geometry routine),

W_i is the i^{th} segment as computed by the geometry routine,

Σ_{Ri} is the removal cross-section (per unit density) for the i^{th} material and is from Library 1 for material M_i, and

Σ_{RR} is the removal cross section (per unit density) for the reference material and is from Library 1 for the material corresponding to the reference material.

The energy index a is set to one, and H^{n**}, the heat generation rate per source point, is set to zero.

4. The neutron moments-method energy spectra[1] F_a^{n*} is generated and the spectral point for energy a,

$$F_a^n = 2.46 \cdot F_a^{n*} \cdot I ,$$

is computed (I is the source-point fission intensity from Library 3 and 2.46 is the number of neutrons per fission). Then, the function D_a^n is replaced by the current value of D_a^n plus F_a^n and the detector print option X is tested.

---

[1] The moments-method attenuations for neutrons have been fitted to a polynomial of the form $4\pi r^2 F_a^n = \exp\{C_1W^4 + C_2W^3 + C_3W^2 + C_4W + C_5\}$ and the coefficients for this polynomial are listed in Library 1 in order of descending energy; the last set is for the dose-rate curve. It has been found necessary to section these curve fits in order to obtain a better fit; hence, two sets of coefficients are shown in Library 1, one for $W \leq BP$, and one for $W \geq BP$ (BP is an arbitrarily chosen segment, and for the data shown in Appendix C the most common value is 60 gm/cm^2).

If X is greater than or equal to 2, the source-point option Q is tested. If Q is 1, then H^{n**} is replaced by the current value of H^{n**} plus the product of F_a^n, δ_a^{nH}(the neutron flux-to-heat conversion factors from Library 1), and hf_a the integrating or histogram factors from Library 1.

5. a is tested; if a is less than a_{max}, the routine goes to Step 4. If $a = a_{max}$, Q is 1, and $X \geq 2$, the current value of H^{n**} is the heat generation rate due to the one source point and this value is to be printed out by the program. If $a = a_{max}$ and $X \leq 2$, the dose rate is to be computed; hence, a is set equal to a_{max+1} and Step 4 is repeated; then Q is tested, and if Q is 1 the dose rate for the source point, $F^n_{a_{max}+1}$, is to be printed out by the program.
6. The source-point index S is tested. If S is less than $S_{max}(S^*)$, the number of source points in the S^{*th} source group (from Library 3), then S is incremented by one and the routine goes to Step 3. If $S = S_{max}$ (S^*), the current values of D_a^n (for a = 1 through a_{max}) are the spectral points for the energy spectra of the neutron number flux due to the S^{*th} source group and the current value of $D^n_{a_{max}+1}$ is the dose rate for this group. These numbers are printed out by the program. If $X \geq 2$, and $Q > 1$ the heat generation rate due to this source group is calculated from

$$H^n = \sum_{a=1}^{a_{max}} D_a^n \, h_a \, \delta_a^{nH},$$

where the parameters are as defined above.

7. S^*, the source-group index, is tested; if S^* is less than S^*_{max} (from Library 3), D_a^{n*} (for a = 1 through a_{max+1}) is replaced by the current value of D_a^n plus D_a and H^{n*} is replaced by the current value of H^{n*} plus H^n; then S^* is incremented by one, and the routine goes to Step 2. If $S^* = S^*_{max}$, the current value of H^{n*} is the heat generation rate due to all source points, the current values of D_a^{n*} ($a = 1$ through a_{max}) are the spectral points of the energy spectrum of the neutron number flux due to all the source points, and $D^{n*}_{a_{max}+1}$ is the total dose rate.

The data generated by this routine for program output are:

1. D_a^n and D_a^{n*} (for a = 1 through a_{max}) - the spectra of the neutron number flux summed over each source group and over all source groups, respectively.
2. $D^{n**}_{a_{max}+1}$, $D^{n}_{a_{max}+1}$, $D^{n*}_{a_{max}+1}$ - the dose rate per source point, per source group, and total, respectively.
3. H^{n**}, H^n, H^{n*} - the heat generation rate per source point, per source group, and total, respectively.

III UTILIZATION

3.1 General

This section lists the required formats for library and problem input for both programs. The data and program-control parameters required for utilization of these programs are grouped into three libraries and a problem deck. In addition, there are two libraries peculiar to the simple-geometry program (C-17), one of which controls readout of information from the library tape, while the other allows deletion of decks from the library tape.

The input data for the program are input in blocks called data files. These data files contain the required computational and/or program-control data and an end-of-file symbol which consists of an asterisk (*) and an identification number. The first piece of data in a file must start on a new card and any alphabetics in the data file must be restricted to the columns shown in the formats (Figs. 3-1 through 3-8). The data is restricted to Columns 2 through 62 of the cards, and the end-of-file symbol should begin in Column 58. (This symbol may be put on a separate card if desired.)

Except for the alphabetics, the conversion digits (the 6, 7, or 8 which must be put in Column 1), and the end-of-file symbol, the data are not restricted to any particular columns within the data field; rather, only the order of the input is important, and more or less data can be put on a card, if desired, than is shown in the formats.

The conversion digit 7 is restricted to use as shown in the formats, and all numbers on a 7 conversion card must be preceded by a sign and must not have a decimal point; this conversion is used for control parameters. The 6 and 8 conversions are used for data input and may be used interchangeably from card to card.

For 6, or fixed-point conversion, numbers are input in normal fashion with signs and decimal points. Signs must be input in all cases and occupy a column in front of their respective numbers. The decimal point is assumed to be to the right of the last digit if it is omitted. A fixed-point number may consist of up to 11 digits, with never more than 10 digits to the right of the decimal point.

For 8, or floating-point conversion, numbers are represented by the sign of the number, followed by from one to eleven digits representing the fraction, followed by the sign of the exponent and one or two digits representing the exponent. Thus, the input number x is defined to be

$$x = F \cdot 10^E ,$$

where $0.1 \leq F < 1, \quad \text{or } F = 0$

and $-37 \leq E \leq 38.$

The above restriction on E is approximate, since this restriction is, in general, dependent on the number of digits of the fraction F. The actual restrictions on input numbers are:

1. For any number x, $|x| \leq 1.7014118216 \times 10^{37}$.

2. The smallest number the program will accept is shown in the table below in terms of the number of digits in the fractional portion:

Number of Digits in Fraction	Minimum Number		Number of Digits in Fraction	Minimum Number	
	Fraction	Exponent		Fraction	Exponent
1	±1	-37	7	±1000000	-31
2	±10	-36	8	±10000000	-30
3	±100	-35	9	±100000000	-29
4	±1000	-34	10	±1000000000	-28
5	±10000	-33	11	±1000000000	-27
6	±100000	-32			

Thus, from the table it is seen that +1 - 37 (1.0×10^{-38}) and -22 - 36 (-2.2×10^{-37}) are allowable input numbers, while +12 - 37 ($+1.2\times10^{-38}$) is not. Note: for floating point conversion, the decimal point is assumed to be at the extreme left of the fraction, but decimals do not appear in this representation.

The error printout from the programs are self explanatory, but the errors found by the executive program (CP-109), are one of the following:

Error Number 1 - The program has found an undefined symbol, illegal double punch, or illegal blank column in the data field of some library or data card.

Error Number 2 - Exponent trouble in floating point.

Error Number 3 - Undefined control punch in Column 1 of some library or data card.

A detailed description of the library and data formats is given in the following sections.

Note: The Library 1 and Library 2 formats, and hence the data for these libraries, are the same for both programs.

Note: All libraries require 7 conversion for the first data file in the library, and 6 or 8 conversion for all other data files.

3.2 Library 1: Material Data (Fig. 3-1)

This library is composed of an arbitrary number of decks, each deck containing all of the data pertaining to one material. Two types of decks may be written into this library. The first of these, which is the type used for neutron reference materials, must contain a *15 data file (neutron differential number-spectra curve-fit coefficients). For this type deck, $a_{max} \neq 0$, and EG $\neq 0$. Each of the other data files of this library (Fig. 3-1) may or may not be listed. The second type of deck is that used for non-reference materials; this deck must contain a *13 data file (neutron heating coefficients). In this case, $a_{max} = 0$, EG = 0 and no *14 or *15 data files may be put in the deck; each of the other data files of this library may or may not be listed. A non-reference material deck may be made into a reference material deck by an appropriate change in a_{max} and EG, and by adding a data file *15. Appendix D gives typical Library 1 deck lists for various materials.

	Columns 1		60-62
First Card	7	LIBRARY DATA (LTYPE = 1) M EG A_{MAX}	*10
Second Card	6/8	Σ_R	*11
Photon	6/8	μ_1 Z_{eff1} $\delta_1^{\gamma H}$	
Energy	6/8	μ_2 Z_{eff2} $\delta_2^{\gamma H}$	
Data	.		
	6/8	μ_{14} Z_{eff14} $\delta_{14}^{\gamma H}$	*12
Flux	6/8	a_{maxEG1} δ_1^{nH} δ_2^{nH} . . . $\delta_{a_{maxEG1}}^{nH}$	
to	6/8	a_{maxEG2} δ_1^{nH} δ_2^{nH} . . . $\delta_{a_{maxEG2}}^{nH}$	
Heat	.		
Factors	6/8	a_{maxEG5} δ_1^{nH} δ_2^{nH} . . . $\delta_{a_{maxEG5}}^{nH}$	*13
Histograms	6/8	hf_1 hf_2 . . . $hf_{A_{MAX}}$	*14
	6/8	$C_{1,1}$ $C_{1,2}$ . . . $C_{1,5}$	
Curve	6/8	$C_{2,1}$ $C_{2,2}$ . . . $C_{2,5}$	
Fit	.		
Valves	6/8	$C_{AMAX+1,1}$ $C_{AMAX+1,2}$ . . . $C_{AMAX+1,5}$	
	6/8	BREAKP	
	6/8	$C_{1,1}$ $C_{1,2}$ . . . $C_{1,5}$	
	6/8	$C_{2,1}$ $C_{2,2}$ . . . $C_{2,5}$	
	.		
	6/8	$C_{AMAX+1,1}$ $C_{AMAX+1,2}$ . . . $C_{AMAX+1,5}$	*15

FIGURE 3-1. LIBRARY-TYPE 1

Each Library 1 deck may contain the following data files:

A. Control Parameters (*10). This data file consists of one card (Fig. 3-1) containing the following:

1. Library type identification, i.e., LIBRARY DATA+1. (Columns 2 through 16)
2. M, the material number (a positive integer). This number serves as a deck identification number, and hence the decks should be numbered consecutively. This number is also used by the program to determine which material deck is to be identified with a given region for a particular problem (Figs. 3-7 and 3-8).
3. EG, neutron-energy-mode identifier. This number is input as an integer, $0 \leq EG \leq 5$. Each non-zero value of EG identifies a particular set of neutron energies, the first four of which are listed in Table 3-1. The number EG is non-zero only if the material deck contains a *15 data file (neutron differential number-spectra curve-fit coefficients) and, in this case, EG refers to the set of neutron energies (from Table 3-1) to which the neutron curve fits correspond.
4. a_{max}, the number of energies for which the neutron differential number spectrum is defined in the material deck. a_{max} is non-zero for reference materials only and, in general, $0 \leq a_{max} \leq 10$.

TABLE 3-1

Neutron Energy Intervals and Histogram Factors for the First Four Neutron-Energy Modes

$\bar{E}$ (Mev)	h^n (Mev)	E_{min} (Mev)	E_{max} (Mev)
MODE 1 (Standard)			
0.33	0.565	0.1	0.665
1	0.825	0.665	1.5
2	1	1.5	2.5
3	1	2.5	3.5
4	1.5	3.5	5
6	2	5	7
8	2	7	9
10	3	9	12
14	4	12	16
18	4	16	20
MODE 2			
0.33	0.61	0.1	0.71
1.1	1.19	0.71	1.9
2.7	2.45	1.9	4.35
6.0	4.1	4.35	8.45
10.9	4.9	8.45	13.35

$\bar{E}$ (Mev)	h^n (Mev)	E_{min} (Mev)	E_{max} (Mev)
MODE 3			
0.33	0.432	0.1	0.532
0.734	0.75	0.532	1.282
1.63	0.853	1.282	2.135
3.64	2.4	2.135	4.535
5.43	2.23	4.535	6.765
8.1	3.335	6.765	10.1
12.1	4.95	10.1	15.05
18	4.95	15.05	20
MODE 4			
0.33	0.43	0.1	0.53
0.73	0.385	0.53	0.915
1.10	0.45	0.915	1.365
1.63	0.67	1.365	2.035
2.44	1.005	2.035	3.021
3.64	1.495	3.021	4.535
5.43	2.23	4.535	6.765
8.10	3.325	6.765	10.09
12.08	4.96	10.09	15.05
18.02	4.95	15.05	20

B. <u>Removal Cross Sections (*11)</u>

Fast neutron removal cross sections are in units of cm^2/gm. (The cross sections for the various material decks are from Reference 8.)

C. <u>Gamma Data (*12)</u>

If a Library 1 deck contains a *12 data file, then each of the elements listed below must be put in, even though these data are input as zeros. These data are input in order of descending energy and the energy sets used are listed in Table 3-2. The coefficients in this data file are:

1. μ_1 through μ_{14}, gamma-ray attenuation coefficients or mass absorption coefficients in units of cm^2/gm. These coefficients have been interpolated from Reference 6.
2. $Zeff_1$ through $Zeff_{14}$, effective atomic number. For elemental materials, these are the atomic number of the material, hence, are independent of energy; but for mixtures and compounds, Zeff is found by first computing the absorption coefficient per electron (using the formulae below), then from the computed μ_e an interpolation of Z is made as a function of the absorption coefficient per electron for the elements. This Zeff is, in general, a function of photon energy.

   The absorption coefficient per electron for mixtures and compounds is given by

TABLE 3-2

Initial and Final Gamma-Ray Energies, Their Dependence on a and b, and the Relationship to a and b of the Numerical Index Used in Library 2 on the Coeffients A and hg.

	E_b	10	9	8	7	6	5	4	3	2	1.375	1	0.75	0.5	0.25
	b	1	2	3	4	5	6	7	8	9	10	11	12	13	
a	E_a														
1	10	1													
2	9	2	3												
3	8	4	5	6											
4	7	7	8	9	10										
5	6	11	12	13	14	15									
6	5	16	17	18	19	20	21								
7	4	22	23	24	25	26	27	28							
8	3	29	30	31	32	33	34	35	36						
9	2	37	38	39	40	41	42	43	44	45					
10	1.375	46	47	48	49	50	51	52	53	54	55				
11	1	56	57	58	59	60	61	62	63	64	65	66			
12	0.75	67	68	69	70	71	72	73	74	75	76	77	78		
13	0.5	79	80	81	82	83	84	85	86	87	88	89	90	91	
14*	0.25	92	93	94	95	96	97	98	99	100	101	102	103	104	**105

*The coefficients hf_{92}-hf_{105} are used for the dose- and heating-rate integrations.

**No set of A_{105} is used.

$$\mu_e = \sum_{i=1}^{N} \mu_{ai} Z_i H \quad ,$$

where

N is the number of elements in the material,

$$H = \frac{1}{\sum_{i=1}^{N} \beta_i Z_i} ,$$

β_i = the weight fraction of the $i\underline{th}$ element for mixtures

$= \frac{n_i A_i}{\sum_i n_i A_i}$ where n_i equals the number of atoms of the $i\underline{th}$ kind (which has atomic weight A_i) in a molecule for compounds,

μ_{ai} is the absorption coefficient (cm^2/gm), and

Z_i is the number of electrons per gram of the $i\underline{th}$ material.

3. $\delta_1^{\gamma H}$ through $\delta_{\alpha_{max}}^{\gamma H}$, gamma-ray flux-to-heat conversion factors. These factors are given by

$$\delta_\alpha^{\gamma H} = E_i(\mu_i - \rho_e \sigma_{si}) \times (1.602 \times 10^{-13} \text{ watts/Mev}),$$

where

E_i = the photon energy for which the coefficients are being computed (in Mev),

ρ_e is the material electron density (in electrons/gm),

σ_{si} is the Klein-Nishina scattering cross section as stated on page 25 of Reference 9 (in cm^2/electron) in hydrogen for the energy E_i, and

μ_i is the gamma-ray attenuation coefficient for the $i\underline{th}$ energy, as defined above.

D. Neutron Flux-to-Heat Conversion Factors (*13)

As stated above, if the Library 1 deck pertains to a non-reference material, the deck must contain a *13 data file (this may be simulated by a card containing one or two zeros and the end-of-file symbol, *13). This data file consists of from one to five sets of fast-neutron flux-to-heat conversion factors and an identifying symbol a_{max} as defined below.

1. a_{maxEG_1}, the number of energies for which the neutron differential number spectrum is defined for neutron energy mode 1.

   $a_{maxEG_2} \ldots a_{maxEG_5}$ are similarly defined for neutron energy modes 2 through 5.

2. δ_a^{NH} through $\delta_{a_{max}}^{NH}$, fast-neutron, flux-to-heat conversion factors. These factors are proportional to group-averaged neutron elastic-scattering cross sections (or other applicable fast-neutron cross sections), and are given by

$$\delta_a^{NH} = \epsilon_{a_1} \bar{\bar{\Sigma}}_{H_1 a_1},$$

where

$\bar{\bar{\Sigma}}_{H_1 a_1}$ is the neutron scattering cross section per unit density averaged over a^{th} energy group of the neutron energy mode 1, and

ϵ_{a_1} is the fraction of the initial neutron's energy dissipated as heat.

A more thorough treatment of these coefficients, and the coefficients for other neutron reactions is given in Appendix B.

3. $\delta^{nH}_{a_1,EG_1}$ through $\delta^{nH}_{a_{max},EG_1}$, . . . , $\delta^{nH}_{a_1,EG_{MAX}}$ through $\delta^{nH}_{a_{max},EG_{max}}$, Fast-neutron flux-to-heat conversion factors for neutron energy modes 2 through 5, respectively. The units of $\delta^{nH}_{i,EG}$ will be watt cm^2/neutron-gm, i.e., the heat in watts, generated by one neutron in traveling one centimeter in a material of unit density.

E. Neutron Reference-Material Data (*14 and *15)

The last two data files (*14 and *15) shown in Figure 3-1 must be listed for all reference materials.

The first of these data files (*14) consists of the neutron histogram factors; these are the numerical integration factors used in the integration over neutron energy required for the neutron heating calculation. This data file consists of:

hf_1 through $hf_{a_{max}}$, neutron histogram factors. These factors are listed only for reference materials, and the energy mode used to derive these factors is that mode used to define the neutron differential number spectra for the material for which the deck is defined.

The second data file (*15) contains the curve-fit coefficients for neutron differential number spectra. In general, it was not possible to fit these spectra to one set of coefficients and, hence, two sets are required along with a break point

BP (if the equivalent thickness $t_{eq} \leq BP$, the first set is used, and if $t_{eq} \geq BP$, the second set is used). This data file consists of:

1. $C_{1,1}$ through $C_{1,5}$, the set of curve-fit coefficients for the neutron differential number-spectra point for the highest energy. Two sets of these coefficients are needed for each energy; one set for $0 \leq t_{eq} \leq BP$, the second for $BP \leq t_{eq} \leq 250\ gm/cm^2$. The coefficients are for the function

$$4\pi t^2\ F(t) = \exp(C_1 t^4 + C_2 t^3 + C_3 t^2 + C_4 t + C_5)$$

where t is to be in gm/cm^2. $C_{2,1}$ through $C_{2,5}$, $C_{3,1}$ through $C_{3,5}$, ..., $C_{a_{max},1}$ through $C_{a_{max},5}$ are the sets of curve-fit coefficients for the remainder of the neutron differential number spectra and are in order of decreasing energy. The set of coefficients $C_{a_{max+1},1}$ through $C_{a_{max+1},5}$ fit the fast-neutron dose rate in the same manner as for the neutron spectra.

Note: All of the neutron dose-rate curves were computed using the flux-to-dose conversion factors set forth in NYO-6269 (Ref. 10). The curve-fit coefficients must be input such that the independent variable t will have units of gm/cm^2 and the function $F(t)$ will have units of neutrons/cm^2-sec-Mev per incident neutron for the spectral curves and millirem/hr per incident neutron for the dose-rate curves. The data from which these coefficients were generated are given in References 11, 12, and 13.

2. BP, curve-fit break point. This number is used to indicate which one of the two sets of curve-fit coefficients for the neutron spectra are to be used to generate the spectra for a particular value of t, since one set of coefficients is defined for $t \leq BP$, and the second for $t \geq BP$. Note that BP has the same units as t; namely, gm/cm^2.

3.3 Library 2: Gamma Data (Fig. 3-2)

This library is composed of one deck which contains gamma-energy values, flux-to-dose conversion factors, coefficients for the curve fits to the differential energy spectra, histogram factors required for both the gamma spectral integration and the integration over energy required in the gamma heating and dose-rate calculations, and the coefficients for the curve fits to the edge corrections of Berger and Doggett (Ref. 7).

Appendix D gives the Library list presently in use at GD/FW.

Library 2 is required to have a data file *20 (edge corrections) and may contain the following data files:

A. Control parameters (*16)

Library-type identification; i.e., LIBRARY DATA ⊬ 2 (Columns 2 thru 16)

B. Gamma-ray initial/final energies, and flux-to-dose conversion factors (*17)

1. E_{a1} through E_{a14}, degraded gamma energies. The fourteen values are listed in Table 3.2.

2. E_{b1} through E_{b14}, initial gamma energies. These are the same as the degraded energies with the exception of the lowest energy (0.25 Mev), which is deleted.

Columns

1						60-62
7	LIBRARY DATA	(LTYPE = 2)	NG1	NG2		*16
6/8	E_{a1}	E_{a2}	. . .	E_{a14}		
6/8	E_{b1}	E_{b2}	. . .	E_{b13}		
6/8	$\int_1 \gamma D$	$\int_2 \gamma D$	. . .	$\int_{amax} \gamma D$		*17
6/8	ZEFF(MAX1)	$A_{1,1}$	$A_{1,2}$	. . .	$A_{1,6}$	
6/8		$A_{2,1}$	$A_{2,2}$	. . .	$A_{2,6}$	
⋮		.	.	. . .	.	
6/8		$A_{104,1}$	$A_{104,2}$	. . .	$A_{104,6}$	*18
6/8	ZEFF(MAX2)	$A_{1,1}$	$A_{1,2}$	. . .	$A_{1,6}$	
⋮		.	.	. . .	.	
6/8		$A_{104,1}$	$A_{104,2}$	. . .	$A_{104,6}$	*18
6/8	ZEFF(MAX3)	$A_{1,1}$	$A_{1,2}$	. . .	$A_{1,6}$	
⋮		.	.	. . .	.	
6/8		$A_{104,1}$	$A_{104,2}$	. . .	$A_{104,6}$	*18
6/8	hf_1	hf_2	. . .	hf_{105}		*19
6/8	ZEFF(MAX4)	$B_{1,1}$	$B_{1,2}$	. . .	$B_{1,6}$	
⋮		.	.	. . .	.	
6/8		$B_{13,1}$	$B_{13,2}$	. . .	$B_{13,6}$	*20
6/8	ZEFF(MAX5)	$B_{1,1}$	$B_{1,2}$	. . .	$B_{1,6}$	
⋮		.	.	. . .	.	
6/8		$B_{13,1}$	$B_{13,2}$	. . .	$B_{13,6}$	*20

FIGURE 3-2. LIBRARY-TYPE 2

NPC 14,525

3. $\delta_1^{\gamma D}$ through $\delta_{a_{max}}^{\gamma D}$, flux-to-dose conversion factors. These are listed in Appendix D.

C. Gamma-ray differential energy spectra coefficients (*18)

1. Zeff(max_1), break point between set $A_{1,xx}$ and set $A_{2,xx}$ of the A's.

2. $A^1_{1,1}$ through $A^1_{1,6}$ ..., $A^1_{104,1}$ through $A^1_{104,6}$, the coefficients for the curve fits to the gamma-ray differential energy spectra for the case $0 \leq Z \leq 26$. These coefficients are for the function

$$\frac{\ln f}{\mu_b r} = A^1(\mu_b r)^2 + A^2(\mu_b r) + A^3(\mu_b r)Z + A^4 Z + A^5 Z^2 + A^6,$$

where

μ_b is the gamma absorption coefficient at energy E_b, and

f(T) is the gamma-ray differential energy spectra as defined in Reference 2.

The dependence of the A's (as shown by the second subscript) on the energy indices a and b (or equivalently on degraded and initial energy) is as shown in Table 3-2.

3. Zeff(max2), break point between set $A_{2,xx}$ and set $A_{3,xx}$ of the A's.

4. The sets of coefficients $A^2_{1,1}$ through $A^2_{1,6}$ ..., $A^2_{104,1}$ through $A^2_{104,6}$ and $A^3_{1,1}$ ..., $A^3_{104,1}$ through $A^3_{104,6}$ are similarly defined for the ranges $26 \leq Z \leq 74$ and $74 \leq 92$, respectively.

5. Zeff(max3), a value as large or larger than any Zeff to be used.

   Note: There are three *18 files, one for each set Zeff(max) and A's.

D. <u>Histogram Factors (*19)</u>

hf_{γ_1} through $hf_{\gamma_{105}}$, histogram factors for the spectral integrations and for the integration over degraded photon energy required for the gamma heat generation rate and dose-rate computations. These factors are input in the same order (as regards initial and final energy indices data) as the differential energy spectra (*18) file.

E. <u>Edge Corrections (*20)</u>

1. $\mu r(\max 1)$, breakpoint between set $B_{1,xx}$ and $B_{2,xx}$ of the B's.

2. $B^4_{1,1}$ through $B^4_{1,6} \ldots$, $B^4_{13,1}$ through $B^4_{13,6}$, the coefficients for the curve fits to the edge corrections to the gamma-ray differential energy spectra for the case $0 \leq \mu r \leq 4$. These coefficients are for the function

$$\ln \gamma = B^1(\mu_b r)^2 + B^2(\mu_b r) + B^3(\mu_b r)Z + B^4 Z + B^5 Z^2 + B^6 ,$$

where

μ_b is the gamma-ray absorption coefficient at energy E_b ,

$g(T)$ is edge correction of Reference 7, i.e.,

$$g(T) = \frac{B(t,t)-1}{B(t,\infty)-1}$$

with the buildup factors in an infinite medium, $B(t,\infty)$, and for a slab, $B(t,t)$, as defined in Reference 4.

3. $B^5_{1,1}$ through $B^5_{1,6}, \ldots, B^5_{13,1}$ through $B^5_{13,6}$ are similarly defined for $4 < \mu r < 20$. The first subscript on the B's refers to initial photon energy and is the energy counter b, as used in (C) above.

4. μr(max2), a value larger than any μ_r to be used.

3.4 Library 3: Source Data

This library is composed of an arbitrary number of decks, each deck containing the source data for a specific problem. Each deck contains from one to six source groups and the required deck-control data. Each source group contains the source-group gamma spectrum (13 quantities which define the gamma spectrum at each source point in the group) and four quantities for each source point in the group, namely, 3 source-point coordinates and the source intensity. Each deck is limited to, at most, 6 source groups and to a total of 500 source points which may be divided among the source groups in any manner. This library is required to have a data file *22.

3.4.1 Library 3 For Simple-Geometry Program (Fig. 3-3).

Library 3 for the simple-geometry program (C-17) contains the following data files:

A. Control parameters (*21)

1. Library-type identification, i.e., LIBRARY DATA + 3 (Columns 2 through 16)

2. N_c, the number of source groups, $1 \leq N_c \leq 6$.

3. N_{s1}, N_{s2}, ..., N_{sNc}, number of source points in the 1st, 2nd, ..., N_cth source group, respectively.

B. Source data (*22). There must be N_c of these fields, one for each source group.

1. S_1, S_2, ..., S_{13}, the gamma-ray spectrum, tabulated in order of decreasing initial photon energy (from 10 Mev to 0.5 Mev).

2. x, y, z, I, the x, y, and z coordinates of the source point and the source intensity; one set of these four numbers must be input for each source point in the source group.

Note: For reactor radiation problems, or any other problem where the neutron portion of the program is to be used, the gamma spectra should be normalized to the number of photons per fission-Mev so that the source intensity may have units of fissions per watt of reactor power. If the program is to be used for secondary-gamma calculations, or calculations of a similar nature where the neutron portion of the program is not used, the normalization of the spectre is arbitrary, since the gamma spectra multiplied by the source intensity must result in units of photons/sec-Mev for a given power level.

Card Columns

1	2 →	62
7	LIBRARY DATA + 3 + N_C + N_{S_1} + ... + $N_{S_{N_C}}$	*21
6	$\pm S_{b_1}$ . . . . $\pm S_{b_{13}}$	
6	$\pm X_{S_1} \pm Y_{S_1} \pm Z_{S_1} \pm I_{S_1}$	
6	$\pm X_{S_2} \pm Y_{S_2} \pm Z_{S_2} \pm I_{S_2}$	
6	" " " "	
6	" " " "	
6	$\pm X_{S_{N_{S_1}}} \pm Y_{S_{N_{S_1}}} \pm Z_{S_{N_{S_1}}} \pm I_{S_{N_{S_1}}}$	*22
6	$\pm S_{b_1}$ . . . . $\pm S_{b_{13}}$	
6	$\pm X_{S_1} \pm Y_{S_1} \pm Z_{S_1} \pm I_{S_1}$	
6	" " " "	
6	" " " "	
6	$\pm X_{S_{N_{S_2}}} \pm Y_{S_{N_{S_2}}} \pm Z_{S_{N_{S_2}}} \pm I_{S_{N_{S_2}}}$	*22

NPC 14,526

FIGURE 3-3. LIBRARY-TYPE 3 FOR THE SIMPLE-GEOMETRY PROGRAM

3.4.2 Library 3 for Complex-Geometry Program (Fig 3-4)

A library 3 for the complex-geometry program (L-63) contains the following data files:

A. Control parameters (*21)

1. Library-type identification, i.e., LIBRARY DATA + 3 (columns 2 through 16).
2. N_c, (defined in Section 2.4.1, A)
3. N_{s1}, N_{s2}, ..., N_{sNc}, (defined in 2.4.1, A)
4. CT_1, CT_2, ..., CT_N, coordinate type

   If CT = 1, the source points are to be input in cartesian coordinates.

   If CT = 2, the source points are to be input in cylindric coordinates.
5. CS_1, CS_2, ..., CS_{Nc}, coordinate system identification number. Each of these numbers must be zero (base coordinate system) or must correspond to the COORN in the problem deck which defines the coordinate system in which the source points for the particular group was defined.

B. Source Data (*22). There must be N_c of these fields, one for each source group.

1. S_1, S_2, S_3, ..., S_{13}, (defined in 3.4.1, B)
2. X, Y or Θ, Z or R, I, the x coordinate, and either the Y and Z coordinates (if CT = 1 for this source group), or the Θ and R coordinates (if CT = 2 for

Columns 1		60-62
7	LIBRARY DATA (LTYPE = 3) N_C N_{S_1} CT_1 CS_1	
7	N_{S2} CT_2 CS_2 . . . N_{SNC} CT_{NC} CS_{NC}	*21
6/8	S_1 S_2 . . . S_{13}	
6/8	(X_1) $(Y_1$ or $\theta_1)$ $Z_1(R)$ I_1	
. . .		
6/8	(X_{NS1}) $(Y_{NS1}$ or $\theta_{NS1})$ $Z_{NS1}(R)$ I_{NS1}	*22
6/8	S_1 S_2 . . . S_{13}	
6/8	(X_1) $(Y_1$ or $\theta_1)$ $Z_1(R) I_1$	
. . .		
6/8	(X_{NS2}) $(Y_{NS2}$ or $\theta_{NS2})$ $Z_{NS2}(R)$ I_{NS2}	*22
. . .		
6/8	S_1 S_2 . . . S_{13}	
6/8	(X_1) $(Y_1$ or $\theta_1)$ $Z_1(R) I_1$	
. . .		
6/8	$(X_{NS_{NC}})$ $(Y_{NS_{NC}}$ or $\theta_{NS_{NC}})$ $Z_{NS_{NC}}(R)$ I_{NS1}	*22

FIGURE 3-4. LIBRARY-TYPE 3 FOR THE COMPLEX-GEOMETRY PROGRAM

this source group), and the source intensity. One set of four numbers must be input for each source point in the source group. All source points in the source group must be in either Cartesian or cylindric coordinates, but not both.

The note above for the simple geometry program also applies here, giving the relationship between the S_b's and I's.

3.5 Deletion and Listout Libraries for the Simple-Geometry Program

The two libraries described below are used with C-17 only.

3.5.1 Library 4: Library Deletion List (Fig. 3-5)

The use of this library is optional, and it is used only to list those decks which are to be deleted from the libraries. The numbers listed in this library are those which appear in Columns 63 through 69 of the decks to be deleted. (The numbers must have plus signs associated with them). The alphabetic DELETE must appear in Columns 2 through 7 of the first card of this library. Fifty or less decks may be deleted by using one Library 4.

3.5.2 Library 5: Deck Listout (Fig. 3-6)

The use of this library is optional, and it is used only to list those decks which are to be printed out from the library tapes. The numbers listed in this library are those which appear in Columns 63 through 69 of the decks to be printed out (the numbers must have plus signs associated with them).

Card Columns
1 2 → 62

1	2 → 62
7	D E L E T E ID_1 ID_2 . . .
7	ID_K ID_{K+1} . . .

FIGURE 3-5. LIBRARY-TYPE 4 (DELETIONS) FOR SIMPLE-GEOMETRY PROGRAM ONLY

Card Columns
1 2 → 62

1	2 → 62
7	L P R I N T ID_1 ID_2 . . .
7	ID_K ID_{K+1} . . .

FIGURE 3-6. LIBRARY-TYPE 5 (LIBRARY LIST OUT) FOR SIMPLE-GEOMETRY PROGRAM ONLY

The alphabetic LPRINT must appear in Columns 2-7 of the first card of this library. Fifty or less decks may be listed using one Library 5.

3.6 Card Identification Field for Library Decks

1. Columns 63 through 66 are left blank. (These are to contain the job number specified by the Computing Laboratory).
2. Column 67 contains the last digit in the year, i.e., 0 for 1960, 1 for 1961, etc.
3. Columns 68 and 69 contain the deck number; starts with 01 for any given set of library input.
4. Columns 70 through 72 contain card numbers; starts with 001 in any given deck.
5. Column 73 contains an L.
6. Columns 78 through 80 contain C17 or L63.

3.7 Problem Deck

This deck contains the program options and that data peculiar to the problem at hand, namely, the parameters required to define the problem geometry, the detector coordinates, the material numbers of the neutron reference materials to be used, and, for L-63, the coordinate systems used to define the geometry, source and detector points.

The geometry for these programs is defined by using a consistent set of x-planes to represent each region in the problem after the method set forth in Section 2.1. In this context, for

the simple geometry program, an x-plane is taken to be an x-value and, for the Cartesian-geometry option, two Y and two Z values (these five numbers are sufficient to determine a particular rectangle with respect to the assumed coordinate system), or, for the cylindric geometry option, two R values (these 3 numbers are sufficient to determine a particular circular annulus with respect to the assumed coordinate system). Thus, two adjacent x-planes, assuming linear interpolation, or circular interpolation for the spherical option in L-63, between analogous Y and Z values or R values, form a volume element, and each region is built up of these volume elements. Similar definitions hold for the complex-geometry program.

3.7.1 Problem Deck for the Simple-Geometry Program (Fig. 3-7)

The problem deck for the simple-geometry program (C-17) contains the following data fields:

Note: In this deck the *6 and *8 data files require 7 conversion; all other files use either 6 or 8 conversion.

A. Control parameters (*6)

This file contains the following:

1. Deck identification, i.e., the alphabetics PROBLEM DATA must appear in Columns 2 through 13.
2. ID_2 and ID_3, the identification of the decks of Libraries 2 and 3 to be used in this problem. These are the numbers contained in Columns 63 through 69 of these libraries.

Card Columns 1	2 →	62
7	PROBLEM DATA $+ ID_2 + ID_3 + N_R + N_{RM} + U$	*6
6	REGN 0 1 $- M + P_a + N_x + \underline{K} + K_{min}$	
	$\pm X_1 \pm Y_{min}(R_i)_1 \pm Y_{max}(R_o)_1 \pm Z_{min_1} \pm Z_{max_1}$	
6	$\pm X_{N_X} \pm Y_{min}(R_i)_{N_X} \pm Y_{max}(R_o)_{N_X} \pm Z_{min_{N_X}}$	*7
6	REGN $N_R + M + P_a$	*7
7	REFMAT $+ H_1 + H_2 \cdot \cdot \cdot \cdot \cdot \cdot + H_{N_{RM}}$	*8
6	DETECT $+ N_D$	
	$\pm X_{D_1} \pm Y_{D_1} \pm Z_{D_1} + \underline{\overline{X}}_1 + \underline{\overline{Y}}_1 + \underline{\overline{\Omega}}_1$	
6	$\pm X_{D_{N_D}} \pm Y_{D_{N_D}} + Z_{D_{N_D}} + \underline{\overline{X}}_{N_D} + \underline{\overline{Y}}_{N_D} + \underline{\overline{\Omega}}_{N_D}$	*9

FIGURE 3-7. PROBLEM DECK FOR THE SIMPLE-GEOMETRY PROGRAM

3. N_R, the number of geometric regions defined for the problem. This includes the dummy region which must always be defined and must be the last region.

4. N_{RM}, the number of neutron calculations to be made or, equivalently, the number of neutron reference materials listed (by material number M) in the problem deck. $N_{RM} = 0$ if no neutron calculation is to be made, and, in general, $0 \leq N_{RM} \leq 10$.

5. U, gamma calculation option.

   U = 1 - differential energy spectra for an infinite media used

   U = 2 - edge-corrected differential energy spectra used

   U = 3 - both calculations (1 and 2) made.

B. Volume Parameters (*7)

This field contains all of the parameters required to define one volume of the geometry. Each of these fields, excepting the last one (which defines the dummy region), must contain the following:

1. Region identification. The alphabetics REGN must appear in Columns 2 through 5 of the first card in a *7 field, and Columns 6 and 7 of this card must contain a two-digit region identification number (the N_R regions must be numbered in sequential order as they appear in the deck, i.e., 01, 02, ..., N_R).

2. M, material number. The number of the Library 1 deck which corresponds to the material for which the region is defined.

3. ρ, the density of the material M in the region (gm/cm^3).

4. N_x, the number of x-planes used to define the region.

5. K, geometry-type parameter.

   K = 1 - region is cylindric

   K = 2 - region is Cartesian

6. K_{min}, boundary uncertainty parameter (cm). The stepping-point method precludes an exact determination of the points at which the "source-detector line" intersects the region bounds. Hence, it is necessary to input a number to define the greatest allowable error in the boundary determination. Since the stepping-point method is an iterative technique, an excessively small value of K_{min} will require a large number of iterations and, hence, will increase the machine time required to run the problem. On the other hand, too large a value for K_{min} will result in excessive error in the boundary determination and, hence, the final results will be in error due to these uncertainties in the determination of the boundaries.

One method of determining K_{min} is to require that it be smaller than some fraction, say 0.01, of the smallest relaxation length (either neutron or photon) of the particles in the materials of the system being considered. For example, consider a system composed of the GTR and a shield of water, aluminum, iron and Portland concrete. From Reference 8, the removal cross sections for the above are: 0.0949 cm^{-1}, 0.101 cm^{-1}, 0.0788 cm^{-1}, 0.1688 cm^{-1} and 0.0801 cm^{-1}, respectively. From Reference 14, the largest values of the photon attenuation coefficients (in each case for a photon energy of 0.25 Mev) are: 0.225 cm^{-1}, 0.126 cm^{-1}, 0.302 cm^{-1}, 0.918 cm^{-1}, and 0.270 cm^{-1}, respectively. The largest of these numbers (the attenuation coefficient for $E = 0.25$ Mev in iron) is 0.919 cm^{-1} which corresponds to a relaxation length of 1.089 cm. Hence, if $K_{min} = .01 \times 1.089 =$ 0.01089 cm, then the boundaries will be determined so that the error involved in determining the source-detector path length in any region will be less than 0.01 of a relaxation length for either photons or neutrons in this region.

7. The following data (in cm) must be entered for each of the N_x x-planes used to define the region:

a. x_p, the x-plane x-coordinate

Note: the x-planes for a given region must be listed in order of increasing x_p.

b. Either Y_{min}, Y_{max}, Z_{min}, and Z_{max}, the x-plane bounds for a Cartesian region (if K = 2), or R_{in} and R_o, the x-plane bounds for a cylindric region (if K = 1).

The last region (or dummy region) contains only Items 1, 2, and 3 above.

C. Neutron reference material numbers (*8)

This field contains N_{RM} material numbers, each of which corresponds to a material deck containing a *15 data field. (This field must contain the alphabetic REFMAT in Columns 2 through 7 of the first card of the field).

D. Detector and program option parameters (*9)

This data file contains the following:

1. Field identification. The alphabetic DETECT must appear in Columns 2 through 7 of the first card of this field.
2. N_D, the number of detector points for the problem.
3. The following data are input for each of the N_D detector points:

   a. x_d, y_d, and z_d, detector point coordinates

   b. X, the detector option

      X = 1 - Spectrum and dose will be calculated.

      X = 2 - Spectrum, heat, and dose will be calculated.

      X = 3 - Spectrum and heat will be calculated.

c. Y, the radiation-type option

Y = 1 - Geometry print. The source-detector distance and penetration distance through all non-void materials will be printed for each source-detector pair.

Y = 2 - Gamma-ray data only will be computed.

Y = 3 - Gamma-ray and neutron data will be computed.

Y = 4 - Neutron data only will be computed.

d. Q, the source point option

Q = 1 - Data for each source point as well as data summed over each source group and over all source groups will be printed.

Q = 2 - Data summed over each source group and over all source groups will be printed.

3.7.2 Problem Deck for the Complex-Geometry Program (Fig. 3-8)

The problem deck for the complex geometry program (L-63) contains the following data file:

A. Control parameters (*6)

This field contains the following:

1. Deck identification (as defined in 3.7.1-A)
2. ID_2 and ID_3 (as defined in 3.7.1-A)

Columns
1

7	PROBLEM DATA ID_2 ID_3 NMR NRM U CSMAX	*6
7	MASTER (MASTN=1) M NX CT CS NREG	
6/8	ρ K_{MIN} X_1 $(Y_{MIN}, Y_{MAX}, Z_{MIN}, Z_{MAX});(Y_1, Z_1, Y_2, Z_2, Y_3, Z_3, Y_4, Z_4);(Rin, Ro);(Rin, Ro, \Theta_1, \Theta_2);$ $(Rin1, Rin2, \Theta_1, \Theta_2, Ro1, Ro2);(Ro1, Ro2, \Theta_1, \Theta_2, Rin);(Rin1, Rin2, \Theta_1, \Theta_2, Ro)$	
. . .	. . .	
6/8	$X_{NX}(Y_{MIN}, Y_{MAX}, Z_{MIN}, Z_{MAX});(Y_1, Z_1, Y_2, Z_2, Y_3, Z_3, Y_4, Z_4);(Rin, Ro);(Rin, Ro, \Theta_1, \Theta_2);$ $(Rin1, Rin2, \Theta_1, \Theta_2, Ro1, Ro2);(Ro1, Ro2, \Theta_1, \Theta_2, Rin);(Rin1, Rin2, \Theta_1, \Theta_2, Ro)$	*7
7	REGION (REGN=1) M NX CT CS NSUB	
6/8	ρ K_{MIN} X_1 [Corresponding values of Y,Z,R, or Θ]	
. . .	. . .	
6/8	X_{NX} [Corresponding values of Y,Z,R, or Θ]	*7
7	SUBREG (SUBN=1) M NX CT CS	
6/8	ρ K_{MIN} X_1 [Corresponding values of Y,Z,R, or Θ]	
. . .	. . .	
6/8	X_{NX} [Corresponding values of Y,Z,R, or Θ]	*7
. . .		
7	SUBREG (SUBN=NSUB) M NX CT CS	
. . .		
7	REGION (REGN=2) M NX CT CS NSUB	
. . .		
6/8	MASTER (MASTN=NMR) (Mdummy) (ρ dummy)	*7

	REGION (REGN-Z) M NX CT CS NSUB	
. . . . . .		
6/8	MASTER (MASTN=NMR) (Mdummy) (ρ dummy)	*7
7	REFMAT RM_1 RM_2 . . . RM_{NRM}	*8
7	DETECT d*m D_1 CT_1 CS_1 D_2 CT_2 CS_2 ... D_{d*m} CT_{d*m} CS_{d*m}	*9
6/8	(X_1) (Θ_1 or Y_1) (R_1 or Z) $\bar{X}$ $\bar{Y}$ Q	
. . .		
6/8	(X_{D1}) (Θ_{D1} or Y_{D1}) (R_{D1} or Z) $\bar{X}$ $\bar{Y}$ Q	
6/8	(X_1) (Θ_1 or Y_1) (R_1 or Z) $\bar{X}$ $\bar{Y}$ Q	*9
. . .		
6/8	(X_{D2}) (Θ_{D2} or Y_{D2}) (R_{D2} or Z) $\bar{X}$ $\bar{Y}$ Q	*9
. . .		
6/8	(X_{Dd*m})(Θ_{Dd*m} or Y_{Dd*m})(R_{Dd*m} or Z) $\bar{X}$ $\bar{Y}$ Q	*9
6/8	SYSTEM $COORN_1$ Xo Yo Zo X_X Y_X Z_X X_Y Y_Y Z_Y	
6/8	$COORN_2$ Xo Yo Zo X_X Y_X Z_X X_Y Y_Y Z_Y	
. . .	. . .	
6/8	$COORN_{CSMAX}$ Xo Yo Zo X_X Y_X Z_X X_Y Y_Y Z_Y	*10
	NOTE: $\sum NMR + \sum NREG + \sum NSUB \leq 500$ $\#M's \leq 30$	

FIGURE 3-8. PROBLEM DECK FOR THE COMPLEX-GEOMETRY PROGRAM

3. N_{MR}, the number of master regions defined for the problem. This includes the "dummy volume" which must be listed as a master region and also must be the last master region.

4. N_{RM} (as defined in 3.7.1-A)

5. U (as defined in 3.7.1-A)

6. CS_{max}, the number of coordinate systems used to define the problem geometry (the base system is not counted).

Note: This data file requires 7 conversion.

B. Volume parameters (*7)

This field contains all of the parameters required to define one volume of the geometry. Each of these fields excepting the last one (the dummy volume which must be listed as a master region) must contain the following:

1. The alphabetic identification

   MASTER for master regions,

   REGION for regions, or

   SUBREG for subregions

   in Columns 2 through 7 of the first card of the file.

2. N_R, the volume number, which must be preceded by a plus sign. Volumes must be numbered consecutively by type; that is, the first master region is numbered +1, the second +2, etc. Further, if some master region contains regions, the data files for

these regions must follow the data file of the master region in which they are contained, and these regions are numbered starting with +1. If some region contains subregions, the same procedure is followed, that is, the data files for the subregions follow the data file for the region and they are numbered consecutively, starting with +1.

3. M (as defined in 3.7.1-B)
4. N_x (as defined in 3.7.1-B)
5. CT, the coordinate type used to define the volume. This parameter is as defined in Section 2.3.2, or 10 b below. A recapitulation of the values for CT is:

   CT = 0 Simple Cartesian cross section,
   CT = 1 Complex Cartesian cross section,
   CT = 2 Simple cylindric cross section,
   CT = 3 Complex cylindric cross section,
   CT = 4 Rectilinear cylindric cross section,
   CT = 5 Combination I cylindric cross section,
   CT = 6 Combination II cylindric cross section.
6. CS, the number of the coordinate system used to define the volume. CS must correspond to one of the COORN of problem data file *10.
7. NREG or NSUB, the number of volumes contained in the volume being considered. If the volume is a master

region, then NREG is the number of regions contained in the master region; the subregions, if any, contained in one of these regions are not counted. If the volume is a region, then NSUB is the number of subregions contained in the volume. In any case, $0 \leq NREG \leq 10$, and $0 \leq NSUB \leq 10$. If the volume is a subregion, this item is omitted.

Note: The above items require 7 conversion and, hence, must not appear on the same card as any of the following items (which may have either 6 or 8 conversion).

8. ρ, the density of the material M for the volume (gm/cm^3).

9. K_{min} (as defined in 3.7.1-B)

10. The following data must be entered (in cm) for each of the N_x x-planes used to define the volumes:

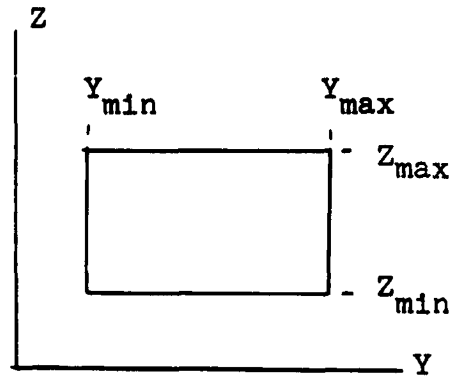
    a. x_p, the x-plane x-coordinate

Note: the x-planes for a given volume must be listed in order of increasing x_p.

    b. Set of numbers required to define an x-plane cross section. These numbers, for each case, are listed below in the order in which they are to appear in the program. Along with each set of numbers there is also shown a sketch of a typical cross section which they are to represent, the required value of CT, and the restrictions on these numbers.

Note: For all of the figures below, the positive x-direction is assumed to be out of the paper.

Simple cartesian (CT = 0)



Input values for each x-plane:

Y_{min}, Y_{max}, Z_{min}, Z_{max}.

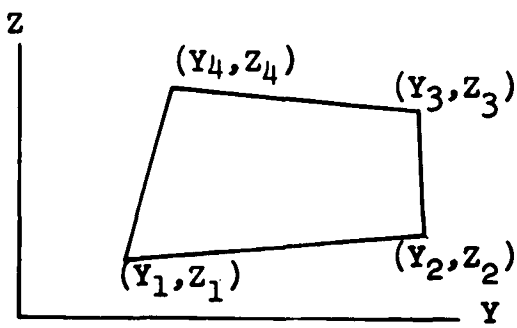
Restrictions:
The defined area is a rectangle whose sides are parallel to either the y or z axis;
$Y_{min} < Y_{max}$, and $Z_{min} < Z_{max}$

Complex Cartesian (CT = 1)

Input values for each x-plane:

Y_1, Z_1 , Y_2, Z_2 , Y_3, Z_3 ,

Y_4, Z_4 .



Restrictions:

(On the points $P_i = (x_p, Y_i, Z_i)$ for i = 1, 2, 3, 4, and the sides $\overline{P_i P_j}$ which is the side with end points P_i and P_j)

Orientation: Neither $\overline{P_1 P_2}$ nor $\overline{P_3 P_4}$ is parallel to the z axis

Neither $\overline{P_1 P_4}$ nor $\overline{P_2 P_3}$ is parallel to the y axis

$(Z_1 Z_2)_{min} < (Z_3 Z_4)_{min}$

$(Y_1 Y_4)_{min} < (Y_2 Y_3)_{min}$

Connectivity: P_1 is adjacent to P_2 and P_4 in the sense shown in the figure above.

Convexity: All internal angles must be less than 180°.

Note: For all of the cylindric regions defined below, the following restrictions apply:

1. The cylinder must be coaxial with the $\bar{x}$ axis of the coordinate system in which it is defined.
2. All angles are to be measured in degrees and

   $0^\circ \leq \Theta_1 \leq \Theta_2 \leq 360^\circ$

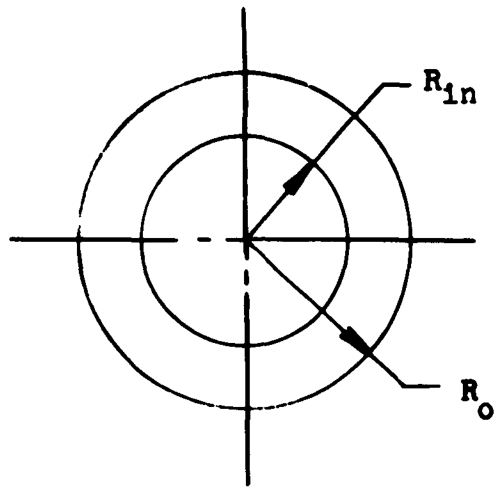
<u>Simple cylinder (CT = 2)</u>

Input values for each x-plane:

R_{in}, R_o.

Restriction:

$R_{in} \leq R_o$.



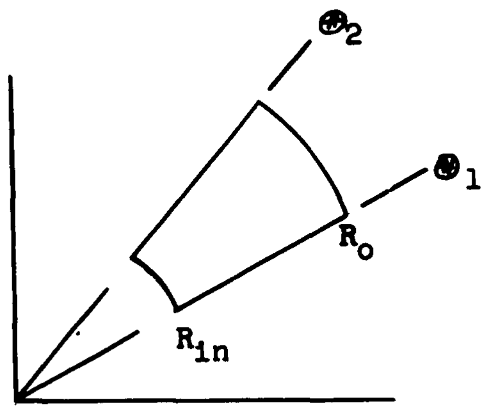
<u>Complex cylinder (CT = 3)</u>

Input values for each x-plane:

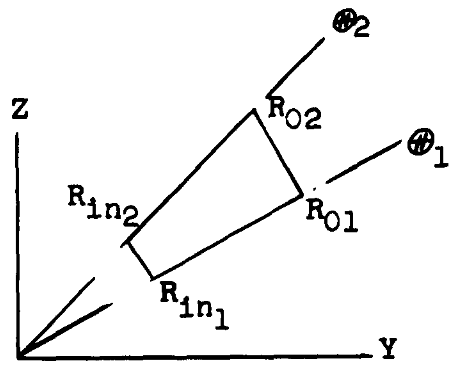
R_{in}, R_o, Θ_1, Θ_2.

Restriction:

$R_{in} \leq R_o$.



Rectilinear cylinder (CT = 4)



Input values for each x-plane:

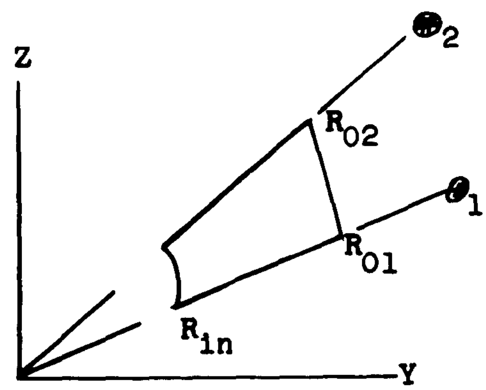
R_{in_1}, R_{in_2}, Θ_1,

Θ_2, R_{01}, R_{02}.

Restrictions:

$R_{in_i} \leq R_{0i} \quad i = 1,2$

Combination I (CT = 5)



Input values for each x-plane:

R_{01}, R_{02}, Θ_1, Θ_2,

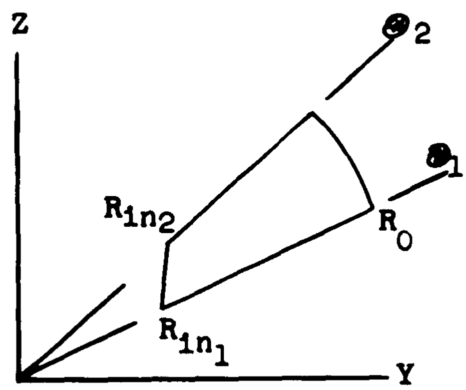
R_{in}.

Restrictions:

$R_{in} \leq R_{01}$

$R_{in} \leq R_{02}$

Combination II (CT = 6)



Input values for each x-plane:

R_{in_1}, R_{in_2}, Θ_1, Θ_2,

R_0.

Restrictions:

$R_{in_1} \leq R_0$

$R_{in_2} \leq R_0$

If CT is preceded by a plus sign, the program will use linear interpolation between x-planes, and cylinders and rectangular pyramids will be generated.

If CT is preceded by a minus sign, the program will generate portions of spheres with the cross sections above.

B'. Volume parameters for the dummy volume (*7)

The last volume defined for a problem must be the dummy volume, the data field for this volume must contain

1. Alphabetic identification, MASTER, in Columns 2 through 7
2. The volume number which must be N_{MR} (see A,3 above)
3. M, (defined in 3.7.1-B)
4. ρ, (defined in B,8 above)

The parameters above are all that is required to define the dummy volume, but it should be noted that, while 7 conversion is required for the first card of other volume data file, 6 or 8 conversion is required for the dummy volume.

C. Neutron reference material numbers (*8)

This data file is the same as the one for the simple-geometry program (3.7.1-C).

D. Detector and program option parameters (*9)

This data file contains the following:

1. Alphabetic identification, DETECT, in Columns 2 through 7 of the first card.
2. d^*_m, the number of detector groups
3. D_1, D_2, ..., D^*_m, the number of detector points in each detector group.

4. CT_1, CT_2, ..., CT_{d_m}, the type of coordinate used to define the detectors of the various groups, i.e.,

CT = 1, Cartesian coordinates

CT = 2, cylindric coordinates

5. CS_1, CS_2, ..., CS_{d_m}, the coordinate system used to define the detectors of the various groups; each CS $\geq$ 0 must correspond to some COORN of data file *10 below.

Note: The above listed parameters compose the first *9 data file in a problem and this file requires 7 conversion. In addition to this file, d_m additional data files are required per problem; these files require 6 or 8 conversion and contain the following for each detector:

1. Detector coordinates (in cm):

   X, Y, Z if CT = 1, or

   X, θ, R if CT = 2.

2. Program option parameters X , Y , and Q (as defined in 3.7.1-D)

E. Coordinate system parameters (*10)

This data file requires 6 or 8 conversion, and contains the following parameters:

1. Alphabetic identification, SYSTEM, in Columns 2 through 7 of the first card of the file)

2. The following data must be input for each of the coordinate systems (except the base system, i.e., CS = 0) used to define source points, detectors, or volumes.

a. COORN, coordinate system number

b. X_o, Y_o, Z_o, coordinates of the origin of the system (in cm) in terms of the base system.

c. X_x, Y_x, Z_x, coordinates of a point on the $+x$ axis of the system 10 cm from the origin in terms of the base system.

d. X_y, Y_y, Z_y, coordinates of a point on the $+y$ axis of the system 10 cm from the origin in terms of the base system.

3.8 Card Identification Field for Problem Decks

1. Columns 63 through 66 are left blank. (These are to contain the Computing Lab job number as specified by the Computing Lab.)
2. Columns 67 and 68 contain the problem deck number, beginning with 01 for any given set of problems.
3. Columns 69 through 72 contain the card number, starting with 0001 for any given problem deck.
4. Column 73 contains the last digit of the year, i.e., 0 for 1960, 1 for 1961, etc.
5. Columns 78 through 80 contain C17 or L63.

APPENDIX A

NOMENCLATURE AND SYMBOLISM FOR GEOMETRY ROUTINE FLOW DIAGRAMS

A-1 Vector Notation and Logic Symbolism

Vector Notation

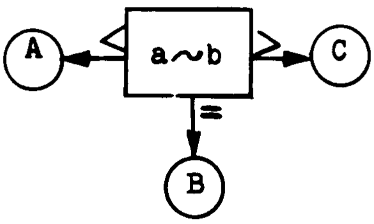
1. All vectors are (3x1) column vectors except $\bar{A}_x$, $\bar{A}_y$, and $\bar{A}_z$ which are (1x3) row vectors.
2. All primed vectors are in terms of the base coordinate system; unprimed vectors are related in the coordinate system of the volume being tested.
3. For two vectors: $\bar{A} = \begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix}$ and $\bar{B} = \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}$,

$$|\bar{A}-\bar{B}| = \sqrt{(x_a-x_b)^2 \quad (y_a-y_b)^2 \quad (z_a-z_b)^2}$$

$$\bar{A}x\bar{B} = \begin{bmatrix} y_a z_b - y_b z_a \\ z_a x_b - z_b x_a \\ x_a y_b - x_b y_a \end{bmatrix}$$

Logic Symbolism

1. $\longrightarrow$ is read as "is replaced by", i.e., $a \rightarrow b$ is read as "a is replaced by b."
2. Branching relationship is defined as in the figure below:



If $a < b$, the program goes to block A

$a = b$, the program goes to block B

$a > b$, the program goes to block C

A-2 Test Function and Nomenclature for the Simple-Geometry Routine

Test Function

The element test function Ψ used in this routine is a linear interpolation on one variable. This function, for the argument R_o, has the form

$$\Psi(R_o) = R_{o,N-1} + \{R_{o,N} - R_{o,N-1}\} \frac{X_P - X_{N-1}}{X_N - X_{N-1}} \qquad \text{(A-1)}$$

where x_n and $R_{o,n}$, and x_{n-1} and $R_{o,n-1}$ are the x-value and outer radius associated with the n^{th} x-plane, and the $n-1^{st}$ x-plane, respectively.

The function Ψ for arguments R_{in}, Y_{min}, Y_{max}, Z_{min}, Z_{max} is similar to Equation A-1 with the exception that the new argument is substituted for R_o.

Nomenclature

B is gamma differential energy spectra control number

C is index: C = 0, volume search: determination of volume in which P lies

C = 1, element search: determination of element in which P lies

C = 2, boundary search: determination of boundary intercept B' for the volume

D is source-detector distance

d is subscript - refers to detector or detector-side boundary of a volume

δ is index of detector point in set

f is index: f = 0, stepping point is on an x-plane

f = 1, stepping point is not on an x-plane

f = 2, stepping point is in base material

i is index of non-void segments such that $M_i \neq M_{i-1}$, numbered so that the closest non-void segment to the source point has $i = 1$.

$\underline{\bar{K}}$ is geometry type number: $\underline{\bar{K}} = 0$, cylindric

$\underline{\bar{K}} = 1$, Cartesian

K is stepping-point increment

$\bar{L}$ is direction cosine vector for P

ℓ_1, ℓ_2, ℓ_3 are components of $\bar{L}$, and P direction cosines for the x, y, and z directions, respectively.

M is material number (M = 0 is void)

$\mathcal{M}$ is reference material number (listed in *8 data file)

m is subscript for maximum

N is volume number (input data)

N_{RM} is number of reference materials (see Sec. 3.1.7-A4)

n is index of x-planes of a volume (n = 1 denotes x-plane with smallest x value)

P is stepping point

$\bar{P}$ is coordinates of stepping point

R_{in}, R_o are x-plane bounds

r is coordinate, cylindric geometry ($r^2 = y^2 + z^2$)

$\bar{S}$ is source-point coordinates

s is subscript - refers to source point or source-side boundary of a volume

$\sim$ is index of source point in set

s* is index of source set in group

T_i is accumulated source-to-i^{th}-boundary-intercept distance

t' is void thickness between stepping point and last completed segment

U is gamma calculation option (Sec. 3.1.7-A5)

V is reference material counter

W is segment length

Y,Z are x-plane bounds (Fig. 2-1)

x,y,z are Cartesian coordinates and vector elements

ρ is material density

Ψ is element test function

A-3 Test Functions and Nomenclature for the Complex-Geometry Routine

Test Functions

1. For cylindric and rectilinear volumes: The element test functions used in this routine are linear interpolation formulae. Ψ represents an interpolation on one variable, and Ξ represents an interpolation on two variables. These formulae are shown below for representative arguments.

$$\Psi(Y_1) = Y_{1,\alpha} + \{Y_{1,\beta} - Y_{1,\alpha}\}\frac{x_p - x_\alpha}{x_\beta - x_\alpha}$$

$$\Xi_{1,2}(\alpha_i Y, Z) = Y_{1,\alpha} + \{Y_{2,\alpha} - Y_{1,\alpha}\}\frac{Z_p - Z_{1,\alpha}}{Z_{2,\alpha} - Z_{1,\alpha}}$$

2. For spherical volumes: The element test functions used in this routine represent a second order interpolation. The functions for a typical argument (representing R_0) are:

$$R_0 = \sqrt{\frac{(R_{0,\alpha}^2 + X_\alpha^2)(X_\beta - X_p) - (R_{0,\beta}^2 + X_\beta^2)(X_\alpha - X_p)}{X_\beta - X_\alpha} - X_p^2}$$

Nomenclature

A is coordinate transformation matrix (see Fig. 2-4 for elements of A)

$\bar{B}$ is coordinates of the boundary intercept being found

$\bar{B}_s$ is coordinates of the source-side boundary intercept of the volume being considered

$\bar{B}_{dq}$ is coordinates of the detector-side boundary intercept of the volume containing the volume being considered

C is index: C = 0, volume search (determination of volume in which P lies)

C = 1, element search (determination of element in which P lies)

C = 2, boundary search (determination of boundary intercept of the volume)

CS is coordinate system identification number (CS = 0 denotes the base coordinate system) input data

CT = 0, Simple Cartesian
1, Complex Cartesian
2, Simple cylinder
3, Complex cylinder
4, Complex-rectilinear cylinder
5, Combination I cylinder
6, Combination II cylinder

D is source-detector distance

$\bar{D}$ is coordinates of detector point (input data)

d (as subscript) refers to detector or detector-side boundary of a volume

d is index of detector point in set

d* is index of detector set in group

E is element

f is index: f = -1, P was in the base material but found a point in a defined volume

f = 0, P not known to be in the base material

f = 1, P is in the base material, $\ell_1 \not< 0$, $\emptyset(\bar{P}*)$ being found

f = 2, P is in the base material, $\ell_1 = 0$, $\emptyset(\bar{P}*)$ being found

f = 3, P is in the base material, $\ell_1 = 0$, $\emptyset(\bar{P}**)$ being found

f = 4, P is in the base material, $\ell_1 \not< 0$, $\emptyset(\bar{P})$ being found

f = 5, P is in the base material, $\ell_1 = 0$, either $\emptyset \not\sim \bar{P}**$ or $\emptyset* \not\sim \bar{P}*$

($\not\sim$ means "does not correspond to")

f = 6, P is in the base material, $\ell_1 \not< 0$, either $\emptyset \not\sim \bar{P}$ or $\emptyset* \not\sim \bar{P}*$

g is index: g = 0, P is not known to be on an x-plane

g = 1, P is on an x-plane

i is index of non-void segments such that $M_i \neq M_{i-1}$, numbered so that the closest non-void segment of the source point has i = 1.

j is index: j = 0, no volume imbedded in the base material impinges upon the source-detector line

j = 1, some volume imbedded in the base material impinges upon the source-detector line

K is stepping point increment

$\bar{L}$ is direction cosine vector for P

ℓ_1, ℓ_2, ℓ_3 are components of $\bar{L}$, and P direction cosines for the x, y, and z directions, respectively

M is material number (M = 0 is void)

m is subscript for maximum

N is volume number (input data)

n is index of x-planes of a volume ($n = 1$ denotes x-plane with smallest x value)

$\bar{O}$ is coordinates of the origin of a coordinate system in terms of the base coordinate system (input data)

P is stepping point

$\bar{P}$ is coordinates of stepping point

$\bar{P}^*$-$\bar{P}^{**}$ is points used in determining whether the source-detector line passes through a subvolume

q is volume type: $q = 0$, master region

$q = 1$, region

$q = 2$, subregion

R_r is element test function (spherical option)

R_{in}, R_o are x-plane bounds (Fig. 2-1)

r is coordinate, cylindric geometry ($r^2 = y^2 + z^2$)

S is source-point coordinates

s (as subscript) refers to source point or source-side boundary of a volume

s is index of source point in set

s^* is index of source set in group

T is accumulated source-to-boundary intercept distance

t is material thickness (along source-detector line)

u is test parameter: $u = y_p$, $CT < 2$

$u = r_p$, $CT > 1$

u_1, u_2 are element test parameters

U_1^*, U_2^* are envelope test parameters

v is test parameter: $v = z_p$, $CT < 2$

$v = \tan^{-1} z_p/y_p$, $CT > 1$

v_1, v_2 are element test parameters

V_1^*, V_2^* are envelope test parameters

W is segment length

x^* is element test function (spherical option)

Y, Z are x-plane bounds (Fig. 2-1)

x, y, z are Cartesian coordinates, and vector elements

α, β, γ, N are x-plane numbers

Γ is x-plane test function

Δ is containing-volume test function; Δ_q is the portion of source-detector line bounded by the source point and the detector-side boundary intercept of the containing volume ($\Delta^* \geq D$)

ϵ is index: $\epsilon = 0$, element test function being computed for X_α

$\epsilon = 1$, element test function being computed for X_β

θ is coordinate, cylindric geometry: $\theta = \tan^{-1} z/y$

ω is index: $\omega = 0$, $|\bar{B}-\bar{S}| < \Delta_q$

$\omega = 1$, $|\bar{B}-\bar{S}| \geq \Delta_q$

Ξ is element test function

Θ is x-plane bounds (Fig. 2-1)

ρ is material density

ϕ is index:

Cylindric Geometry		Cartesian Geometry
	Working on Y or r:	
$\phi_1 = 0$,	$\min(R_{in}) \leq r_p \leq \max(R_o)$	$\min(Y) \leq y_p \leq \max(Y)$
$\phi_1 = 1$,	$r_p < \min(R_{in})$	$y_p < \min(Y)$
$\phi_2 = 2$,	$r_p > \max(R_o)$	$y_p > \max(Y)$

Working on Z or Θ:

$\phi_2 = 0$, $\min(\Theta_1) \leq \theta_p \leq \max(\Theta_2)$ $\qquad$ $\min(Z) \leq z_p \leq \max(Z)$

$\phi_2 = 1$, $\qquad \theta_p < \min(R_{in})$ $\qquad$ $z_p < \min(Z)$

$\phi_2 = 2$, $\qquad \theta_p > \max(R_o)$ $\qquad$ $z_p > \max(Z)$

APPENDIX B

NEUTRON FLUX-TO-HEAT CONVERSION FACTORS

The neutron flux-to-heat conversion factors used for these programs must be the heat generated per incident neutron in a material of unit density, and, hence, these factors will have units of Joules-cm^2/gm.

The heat source due to neutron reactions with nuclei of the target material may be grouped according to the manner in which heat is assumed to be generated by the various reactions. For these programs it is necessary to consider two modes of heat generation, namely, heat generated by secondary (or induced) gamma radiation and heat generated by all other reactions or portions of reactions. (As an example of this grouping, consider the inelastic scattering of neutrons. It is assumed that the recoil energy of the scattering nucleus is dissipated as heat by the second mode and the de-excitation photons generate heat by the first mode.)

The heating rates due to secondary-gamma radiation cannot be computed directly. Using these programs, rather, it is necessary first to determine the neutron flux at a representative number of points in the system and, considering all possible sources of secondary photons, convert these neutrons into secondary-gamma-ray sources using the methods of Reference 1. One may then use these sources together with one of these programs to compute the heat generation rate due to this phenomenon.

The heat generation rate in a given material due to the second mode may be caused by any one or all of the following reactions:

- elastic scattering,
- charged-particle reactions (usually (n,p) or (n,α),
- particle emission from the decay of activated residual nuclei (usually β^+ or β^-),
- inelastic scattering, and
- (n,2n) reaction.

The flux-to-heat conversion factor per incident neutron, as required for the programs, is given by

$$\delta^H = \bar{\bar{E}}\,\bar{\bar{\Sigma}},$$

where

$\bar{\bar{\Sigma}}$ is the group-averaged neutron cross section for the reaction (in cm^2/gm), and

$\bar{\bar{E}}$ is the average energy dissipated as heat per reaction (in Joules).

For the charged-particle reactions (from Ref. 9),

$$\bar{\bar{E}} = E_n + Q - \mathcal{E}$$

where E_n is the initial neutron energy,

Q is the Q value of the reaction, and

$\mathcal{E}$ is the energy given off as secondary photons.

The heat generation rates due to elastic and inelastic scattering and the (n,2n) reaction are derived in the following sections.

B-1 Elastic Scattering

The average energy loss per elastic scatter, $\bar{E}$, as derived in Reference 9, is for isotropic scattering in the center-of-mass coordinate system. This assumption of isotropic elastic scattering is not valid for high neutron energies or for materials of medium-to high mass numbers. Hence, a more exact determination of the average energy loss $\bar{E}$ is required in order to predict heating rates due to fast neutrons.

The derivation of $\bar{E}$ is given in Section 1.2.1 of Reference 9; from this derivation, E is given by

$$\bar{E} = \frac{\int_0^{2\xi E_1} E\, p(E)\, dE}{\int_0^{2\xi E_1} p(E)\, dE} \tag{B-1}$$

where E_1 is the initial neutron energy,

$\xi = 2A/(A+1)^2$ (where A = atomic weight), and

p(E) is the energy-loss distribution of the degraded neutrons.

The energy of the nucleus after collision is related to the scattering angle, θ, by

$$E = E_1 \xi (1 - \cos \theta) \tag{B-2}$$

Hence, the angular distribution of the scattered neutrons may be used in the moments equation to replace p(E); or, since $\bar{E}$ is the quotient of two moments, p(E) may be related to the angular distribution of the neutron scattering cross section. Certain of these distributions for various neutron energies and target materials are given in Reference 15.

The equation for $\bar{E}$ (Eq. B-1) may be rewritten in terms of the scattering angle θ and the elastic scattering cross section $\sigma(E_1, \theta)$ as

$$\bar{E} = \left[\frac{\int_0^{\pi} (1-\cos\theta)\, \sigma(E_1, \theta)\, d(\cos\theta)}{\int_0^{\pi} \sigma(E_1, \theta)\, d(\cos\theta)} \right] \xi E_1$$

or

$$\bar{E} = \left[1 - \frac{\int_{-1}^{1} Z\, \sigma(E_1, Z)\, dZ}{\int_{-1}^{1} \sigma(E_1, Z)\, dZ} \right] \xi E_1$$

where $Z = \cos\theta$.

The cross sections of Reference 8 were plotted against Z and Equation B-3 was used to evaluate $\bar{E}$ from this data. For the elements of lithium, zirconium, tantalum and bismuth, the integral was evaluated numerically using Legendre-Gaussian quadrature. The results are shown in Figure B-1.

Reference 16 is a compendium of cross sections for iron, silicon, aluminum, and oxygen. Among other things, this report lists coefficients for Legendre expansions of the scattering cross sections; these expansions are of the form

$$\sigma(E_1, \theta) = \frac{\sigma(E_1)}{4\pi} \sum_{L=0}^{\infty} (2L+1)\, f_L(E_1)\, P_L(\cos\theta),$$

with f_L defined by

$$f_L = \frac{2\pi}{\sigma(E_1)} \int_{-1}^{1} \sigma(E_1, \theta)\, P_L(\cos\theta)\, d(\cos\theta).$$

By definition, $f_0(E_1) = 1$ so that

$$\sigma(E_1) = 2\pi \int_{-1}^{1} \sigma(E_1, \theta)\, d(\cos\theta),$$

and

$$f_1(E_1) = \frac{\int_{-1}^{1} \sigma(E_1, \theta) \cos\theta\, d(\cos\theta)}{\int_{-1}^{1} \sigma(E_1, \theta)\, d(\cos\theta)}.$$

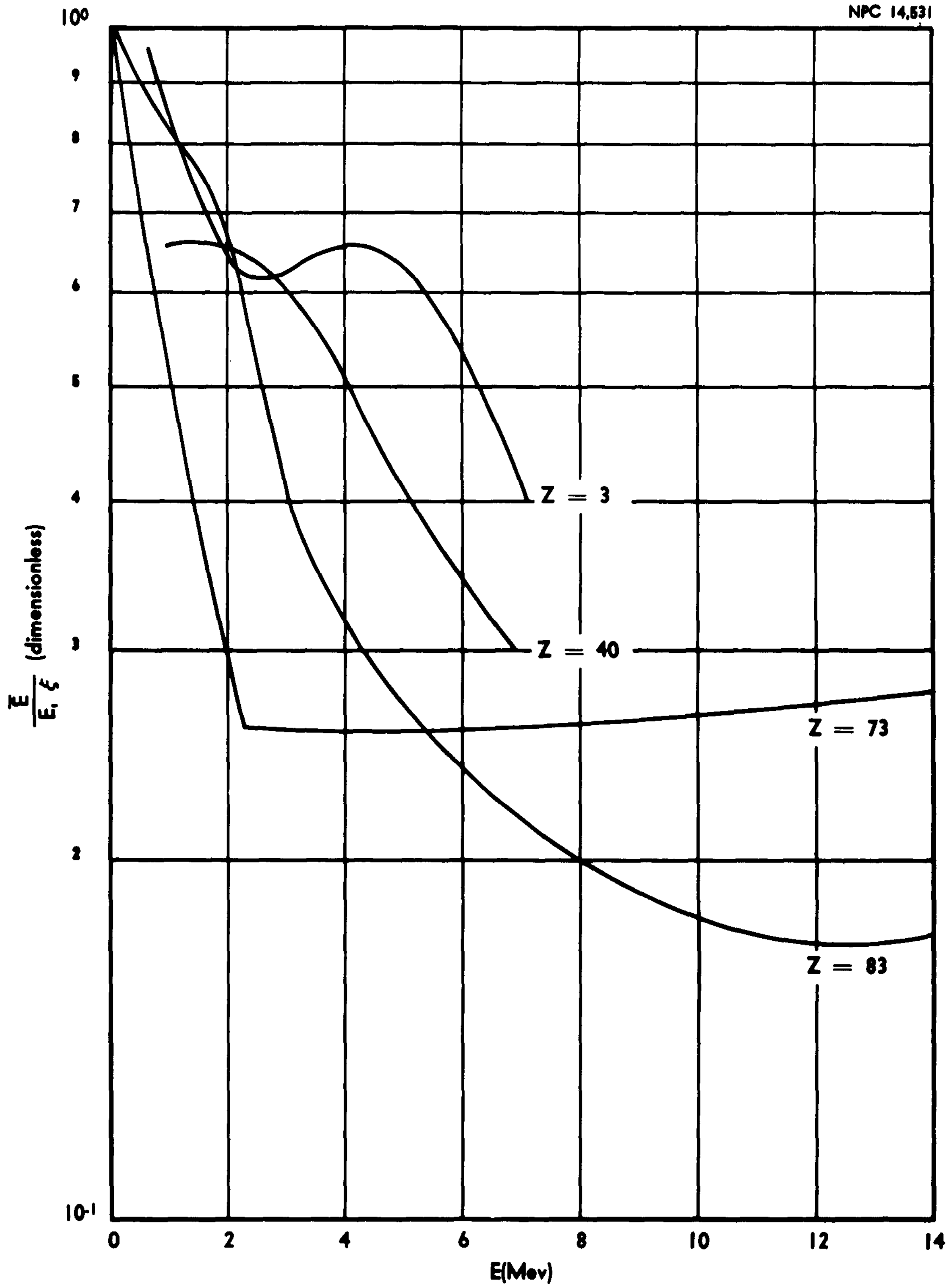


FIGURE B-1. AVERAGE NEUTRON ENERGY LOSS FOR VARIOUS Z NUMBERS

This is the integral term of Equation B-3 where

$$h = \frac{\bar{E}}{\xi E_1} = 1 - f_1(E_1).$$

Values of h for iron, aluminum, and oxygen, computed from data in Reference 16, are shown in Figures B-2 through B-4.

The computed values for h show that the actual heating rates due to elastic scattering may be down by a factor of 10 from those computed assuming isotropic scattering, and, further, the effect is most noticeable at high energy and Z number, as expected from the cross sections.

B-2 Inelastic Scattering and the (n,2n) Reaction

The kinetic energy transfer to the residual nucleus during an (n,n') or (n,2n) reaction is derived from energy and momentum conservation. The final expressions are in terms of the initial neutron energy and either the excitation energy of the residual nucleus or the degraded neutron energies. The expressions in terms of initial neutron energy and excitation energy should be used in all possible cases, i.e., whenever the energies of the resulting photons are known. If the excitation energy is not known, it must be approximated, and this is done by approximating the energies of degraded neutrons (Sec. B-2.3) and finding the recoil energy from an application of the conservation of energy.

Section B-2.4 shows that for the energy range of interest, the excitation energy (and also mass) is essentially the same in both the laboratory and center-of-mass coordinate systems.

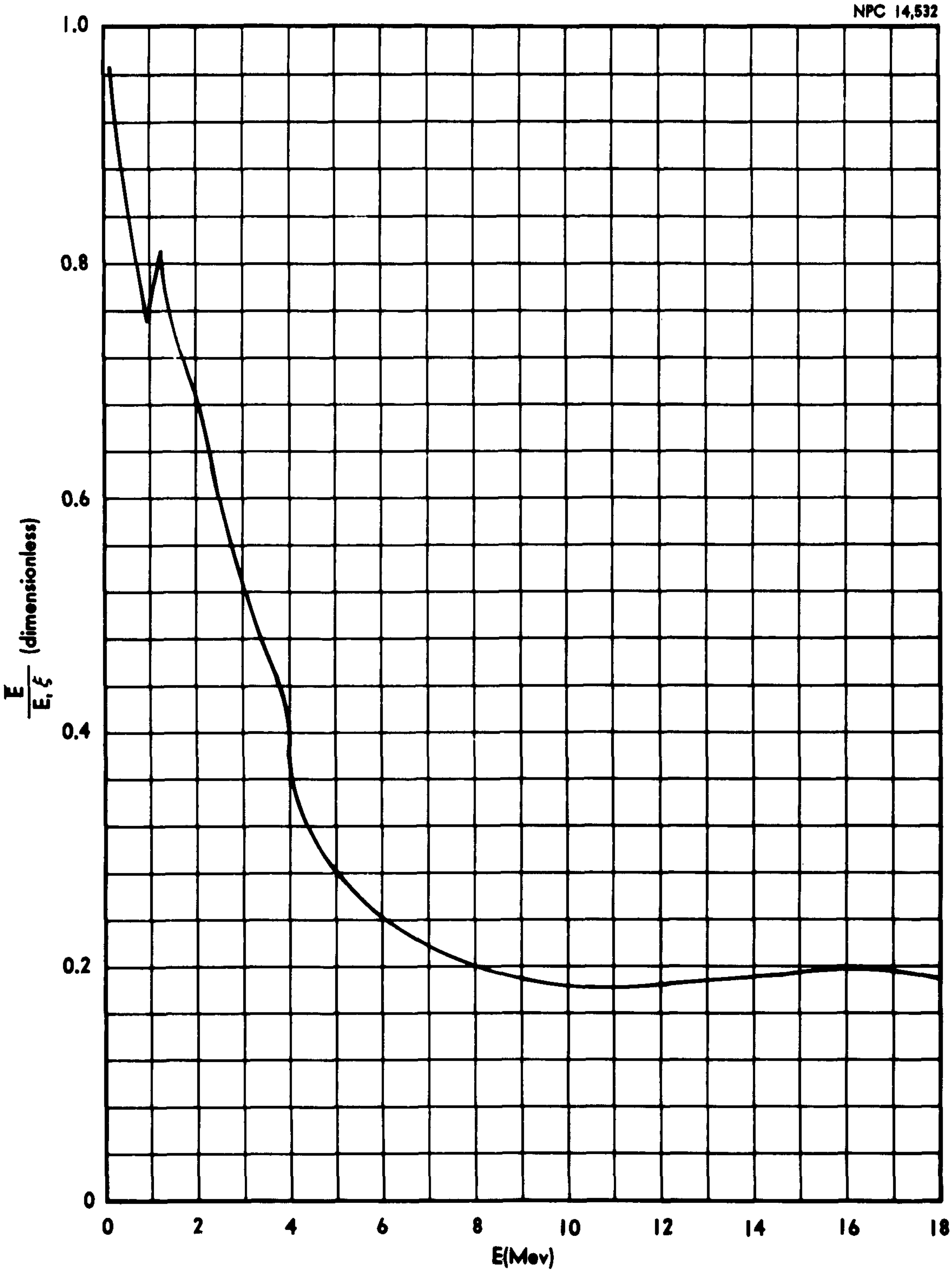


FIGURE B-2. AVERAGE NEUTRON ENERGY LOSS IN IRON

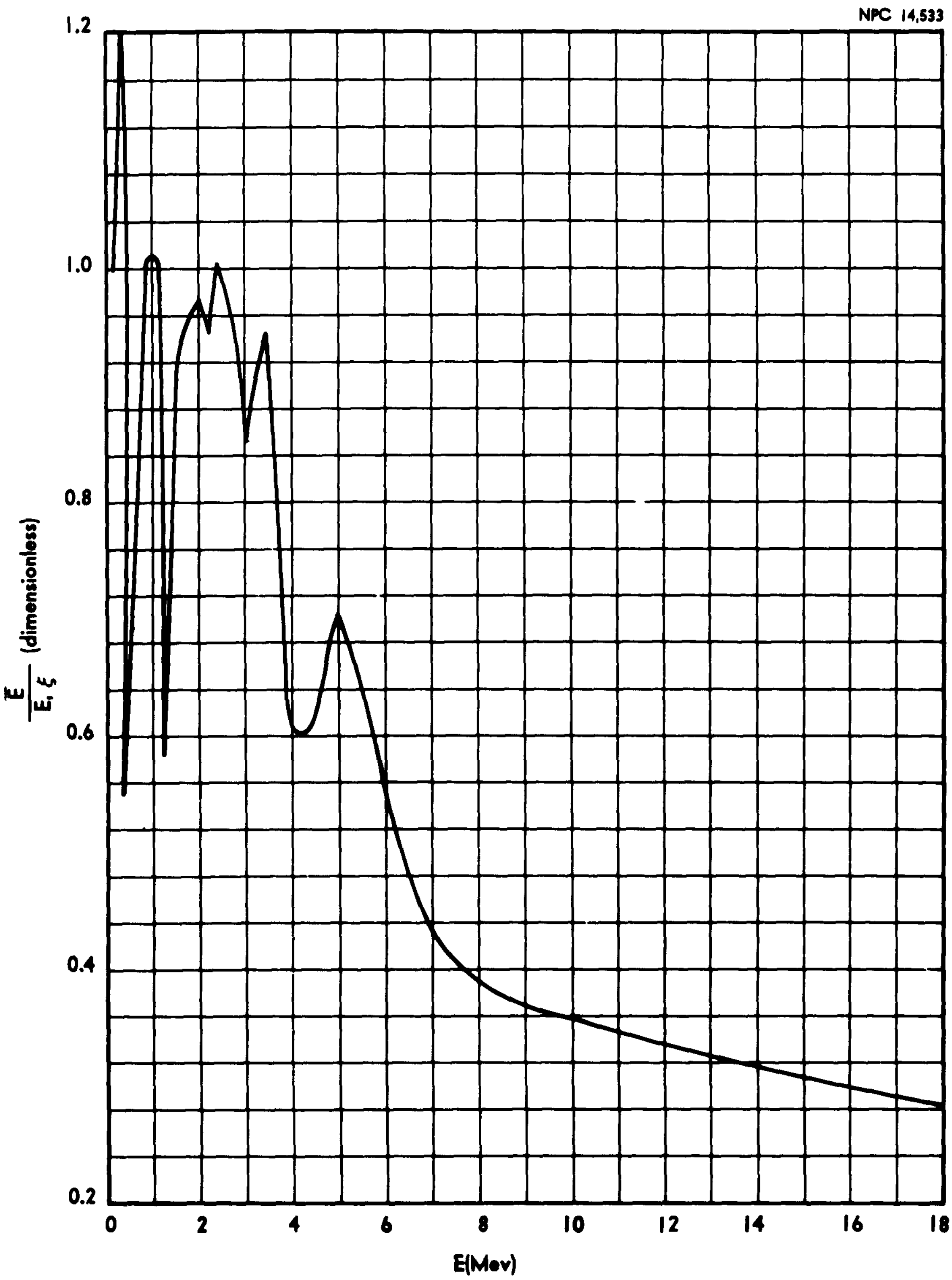


FIGURE B-3. AVERAGE NEUTRON ENERGY LOSS IN OXYGEN

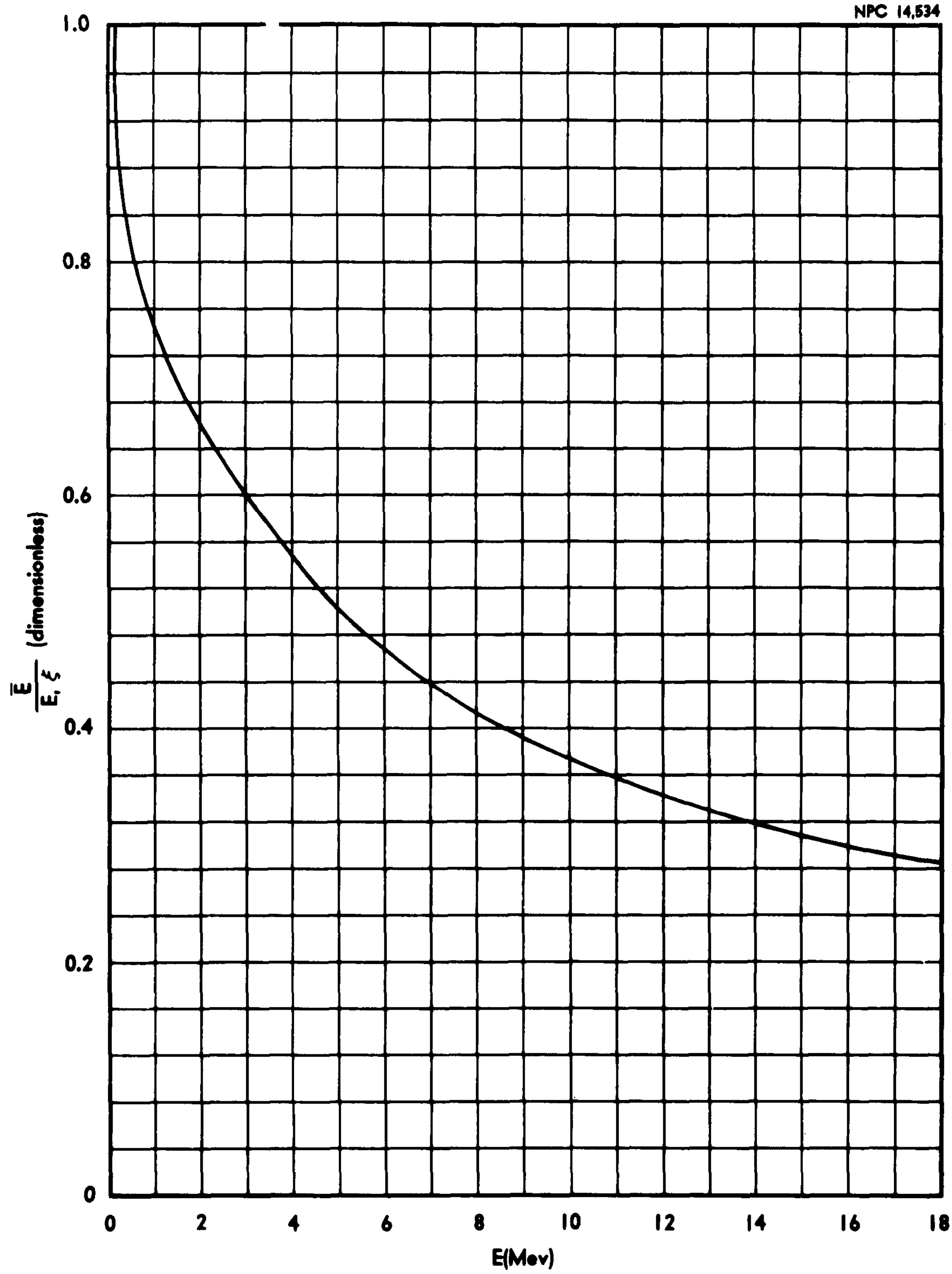
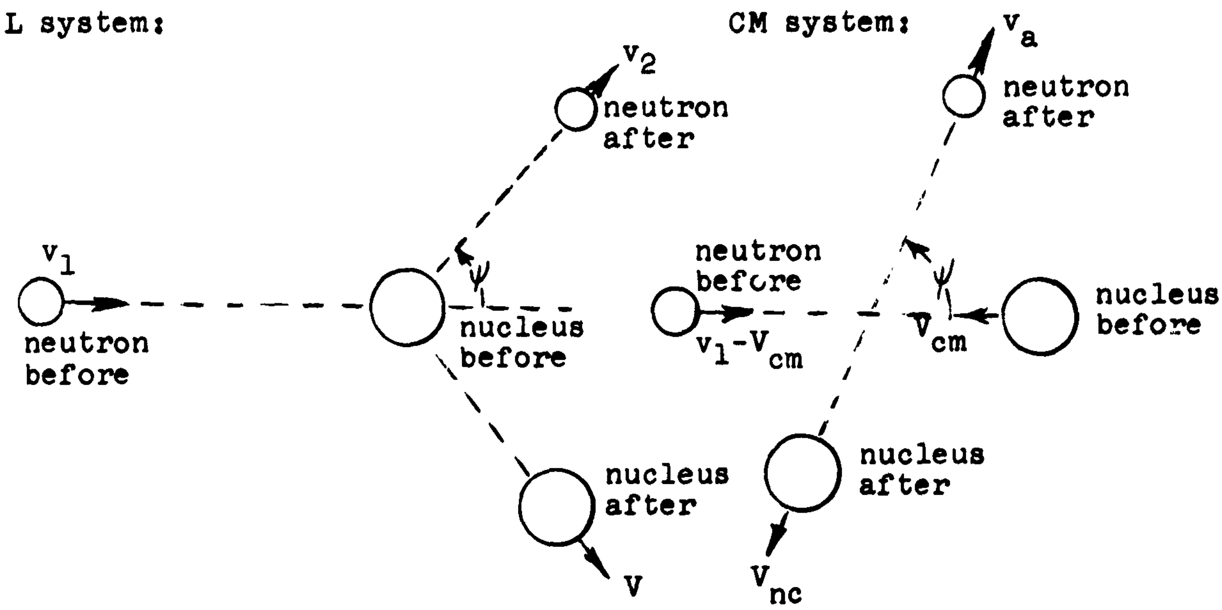


FIGURE B-4. AVERAGE NEUTRON ENERGY LOSS IN ALUMINUM

B-2.1 The (n,n') Reaction

Consider the neutron-nucleus system shown in the sketch.



From conservation of energy and momentum in the CM system,

$$\tfrac{1}{2} m (v_1 - V_{cm})^2 + \tfrac{1}{2} M V_{cm}^2 = \tfrac{1}{2} m v_a^2 + \tfrac{1}{2} M V_{nc}^2 + \mathcal{E}, \quad \text{and } m v_a = M V_{nc}, \tag{B-4}$$

where m is the mass of the neutron,

M is the mass of the nucleus,

ϵ is the excitation energy left with the nucleus, and

the v's are as shown in the sketch.

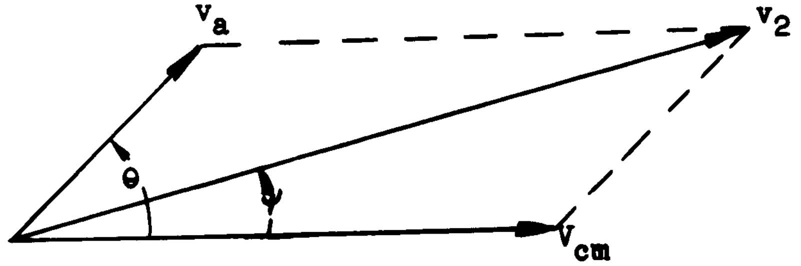
The momentum of the neutron before the reaction, as measured in the L system, must be equal to the momentum of the CM system as measured in the L system; hence,

$$m v_1 = (M + m) V_{cm} .$$

The velocities v_2 and v_a are related by the cosine law:

$$v_2^2 = V_{cm}^2 + v_a^2 + 2\, v_a\, V_{cm} \cos\theta. \tag{B-6}$$

This relationship is shown in the sketch below, which is a superposition of significant portions of the L and CM diagrams sketched above.



Solving Equations B-4, B-5, and B-6 for v_2 in terms of v_1 gives

$$v_2^2 = v_1^2 \left\{ 1 - \xi - \frac{\varepsilon}{E_0} \cdot \frac{A}{A+1} + \xi \sqrt{1 - \frac{A+1}{A}\frac{\varepsilon}{E_0}} \cos\theta \right\}, \tag{B-7}$$

for $E_0 \equiv \frac{1}{2} m v_1^2$,

$A \equiv \frac{M}{m}$, and

$\xi \equiv \frac{2A}{(A+1)^2}$

Energy is conserved in the L system and, therefore,

$$E_0 = E' + E_K + \varepsilon, \tag{B-8}$$

for $E' \equiv \frac{1}{2} m v_2^2$,

$E_K \equiv \frac{1}{2} M V^2$,

And from Equations B-7 and B-8,

$$E_K = E_o \xi \left\{ 1 - \sqrt{1 - \frac{A+1}{A} \frac{\mathcal{E}}{E_o}} \cos\theta \right\} - \frac{\mathcal{E}}{A+1} . \tag{B-9}$$

From Equation B-9,

$$\frac{d\theta}{dE_K} = \frac{\csc\theta}{E_o \xi \sqrt{1 - \frac{A+1}{A} \frac{\mathcal{E}}{E_o}}} .$$

Also, for constant E_o and $\mathcal{E}$,

$$\delta_1 \equiv E_{K\,min} = E_o \xi (1 - \eta) - \frac{\mathcal{E}}{A+1} , \text{ and}$$

$$\delta_2 \equiv E_{K\,max} = E_{k\,min} = 2 E_o \xi \eta ,$$

for $\eta = \sqrt{1 - \frac{A+1}{A} \frac{\mathcal{E}}{E_o}}$.

The average value of E_k is taken to be

$$\overline{E}_K \equiv \frac{\int_{\delta_1}^{\delta_1+\delta_2} p(\theta) \frac{d\theta}{dE_K} E_K \sin\theta \, dE_K}{\int_{\delta_1}^{\delta_1+\delta_2} p(\theta) \frac{d\theta}{dE_K} \sin\theta \, dE_K}$$

where p(θ) is the angular scattering probability function or, equivalently (for this purpose), the angular dependent cross section.

If isotropic scattering in the center-of-mass system is assumed,

$$\overline{E}_K = \frac{\int_{\delta_1}^{\delta_1+\delta_2} E \, dE}{\int_{\delta_1}^{\delta_1+\delta_2} dE} = \delta_1 + 1/2\,\delta_2 ,$$

or

$$\overline{E}_K = E_o \xi - \frac{\mathcal{E}}{A+1} , \tag{B-10a}$$

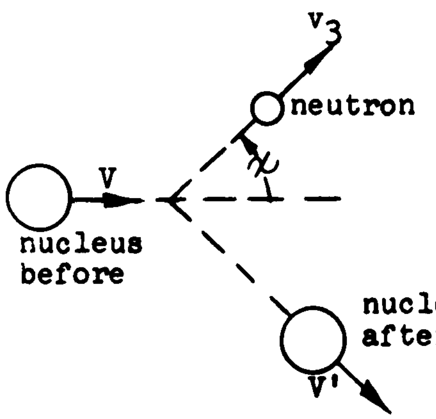
or, in terms of E_o and E,

$$\overline{E}_K = \frac{A-1}{A(A+1)} E_o + \frac{E'}{A} . \tag{B-10b}$$

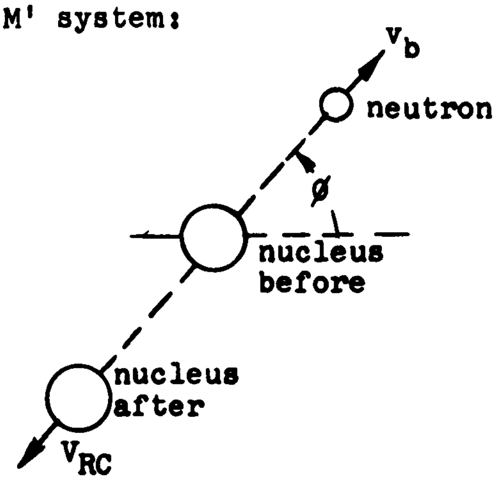
B-2.2 The (n,2n) Reaction

The equations describing the emission of the first neutron are similar to those describing the (n,n') reaction, so that it may be assumed that the kinetic energy of the nucleus before emission of the second neutron, as measured in the L system (see sketch) is given by Equation B-10.

L' system:



CM' system:



From the conservation of energy and momentum in the CM system,

$$D + E = \tfrac{1}{2} M^* V_{RC}^2 + \tfrac{1}{2} m v_b^2 + \mathcal{E}', \quad M^* V_{RC} = m v_b \tag{B-11}$$

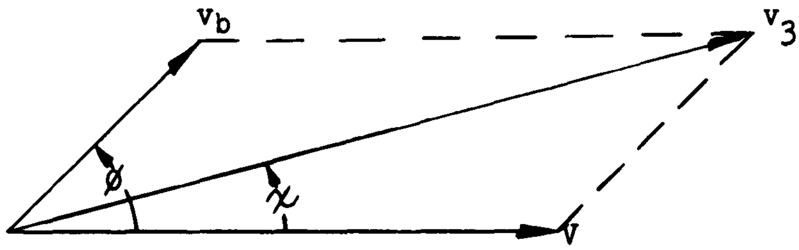
where M^* is the mass of the residual nucleus and, to a good approximation, is given by $M^* \doteq M - m$ (except for calculating D);

$\mathcal{E}'$ is the excitation energy of the residual nucleus;

D is the mass defect and is given by $D = (M - M^* - m)c^2$, and all other parameters are as defined above.

By superimposing portions of the L' and CM' diagrams sketched above, it may be seen v_3 & v_4 are related by

$$v_3^2 = V^2 + v_b^2 + 2 V v_b \cos\phi \,. \tag{B-12}$$



Solving for $E'' \equiv \tfrac{1}{2} m v_3^2$ in terms of E_0, $\mathcal{E}$, and $\eta' \equiv D + \mathcal{E} - \mathcal{E}'$ gives

$$E'' = E_0\xi - \frac{\mathcal{E}}{A+1} + \frac{A-1}{A}\eta' + 2\sqrt{\frac{A-1}{A}\eta'\left\{E_0\xi - \frac{\mathcal{E}}{A+1}\right\}}\cos\phi. \tag{B-13}$$

Conservation of energy in the L' system requires that

$$\eta' = E'' + E' - E_K$$

for

$$E_K' \equiv \tfrac{1}{2} M^* V'^2$$

and, therefore,

$$E_K' = \frac{\eta'}{A} - 2\sqrt{\frac{A-1}{A^2}\eta'\left\{\xi E_0 - \frac{\mathcal{E}}{A+1}\right\}}\cos\phi \,. \tag{B-14}$$

From Equation (B-14)

$$\frac{d\phi}{dE_K'} = \frac{\csc\phi}{2\sqrt{\frac{A-1}{A^2}\eta\left\{\xi E_0 - \frac{\mathcal{E}}{A+1}\right\}}} \,.$$

Also, for constant E_0, $\mathcal{E}$, and η',

$$\delta_1 = E_{K'min} = \frac{\eta'}{A} - 2\sqrt{\frac{A-1}{A}\,\eta'\left\{f E_0 - \frac{\mathcal{E}}{A+1}\right\}}$$, and

$$\delta_2 \equiv E_{K'max} - E_{K'min} = 4\sqrt{\frac{A-1}{A}\,\eta'\left\{f E_0 - \frac{\mathcal{E}}{A+1}\right\}}\,.$$

Analogous to $\bar{E}_K$ for isotropic scattering, the average value of $E_{K'}$ is

$$\bar{E}_{K'} = \frac{\int_{\delta_1}^{\delta_2+\delta_1} E\,dE}{\int_{\delta_1}^{\delta_2+\delta_1} dE} = \delta_1 + 1/2\,\delta_2\,,$$

or

$$\bar{E}_{K'} = \frac{\eta'}{A} = \frac{D+\mathcal{E}+\mathcal{E}'}{A}\,, \qquad \text{(B-15a)}$$

or, in terms of E' and E", the energies of the first and second neutrons emitted, and E_0 the initial neutron energy,

$$\bar{E}_K = \frac{1}{A-1}\left\{E'' - \frac{E'}{A}\right\} - \frac{E_0}{A(A+1)}\,. \qquad \text{(B-15b)}$$

B-2.3 Average Value of the Degraded Neutron Energy

Where a large number of closely spaced energy levels are involved, the methods of statistical mechanics may be used to determine the value of the degraded neutron energy. Thus, this theory will not represent the high end of the degraded neutron spectrum very well since this corresponds to leaving the nucleus in a low excited state where the levels are few and far apart. Further, in lead, iron, and most light elements, the level spacing is large so as to make this method a rough approximation at best.

The differential probability of emission of a neutron with energy E' from a compound nucleus with energy E is

$$dP(E, E') = K\frac{E'}{\Theta} e^{-E'/\Theta} dE',$$

where Θ is the nuclear temperature and

k is a normalization constant.

The average value of E' is taken to be

$$\bar{E}' = \frac{\int_{E*}^{E**} E'dP}{\int_{E*}^{E**} dP},$$

where, for the (n,n') reaction,

E** is the initial neutron energy and

E* is zero;

for the (n,2n) reaction, and for the emission of the first neutron,

E** is the initial neutron energy and

E* is the energy such that the second neutron is emitted with zero energy and the nucleus is left in the ground state (this is the binding energy of the remaining neutron in the nucleus after the first neutron has been emitted);

for the emission of the second neutron,

E** is the initial neutron energy less that energy required to emit the first neutron with zero energy and leave the nucleus in the ground state (this is the initial neutron energy less the binding energy of the last neutron in the compound nucleus) and

E* is zero.

Therefore,

$$\bar{E}' = \theta \, \frac{(\alpha+1)^2+1}{\alpha+1} \cdot \frac{1 - \frac{(\beta+1)^2+1}{(\alpha+1)^2+1} \, e^{\alpha-\beta}}{1 - \frac{\beta+1}{\alpha+1} \, e^{\alpha-\beta}}, \quad \text{(B-16)}$$

for

$\alpha = E^{**}/\theta$, and $\beta = E^{*}/\theta$.

APPENDIX C

NEUTRON REFERENCE MATERIAL COMPARISON

To assist in the selection of base materials to be used in these IBM programs, a series of problems have been run using C-17 in a simple cylindrical geometry. The reactor core was composed largely of carbon, and various shielding materials were placed adjacent to the end of the core. For a shielding material of lithium hydride, detector points were located at various distances from the face of the reactor in the lithium hydride. Eight different base materials were used in computing the dose rate, spectra, and heating rate.

Figure C-1 shows a comparison of heating rates as calculated for the different reference materials. Figure C-2 shows a comparison of dose rates as calculated for the different reference materials.

In order to get some idea as to the reliability of the data calculated by these IBM programs additional calculations have been made of the neutron differential number spectra and compared to those calculated by a multigroup multiregion diffusion code. These comparisons are shown in Figures C-3, C-4, C-5, C-6, and C-7. It is apparent that for "0" distance from the core face the non-hydrogenous reference materials differential number spectra calculations do not agree with those calculated by the diffusion code. This is due to the inability to fit the moments data accurately for penetration distances of less than 10 cm^2/gm.

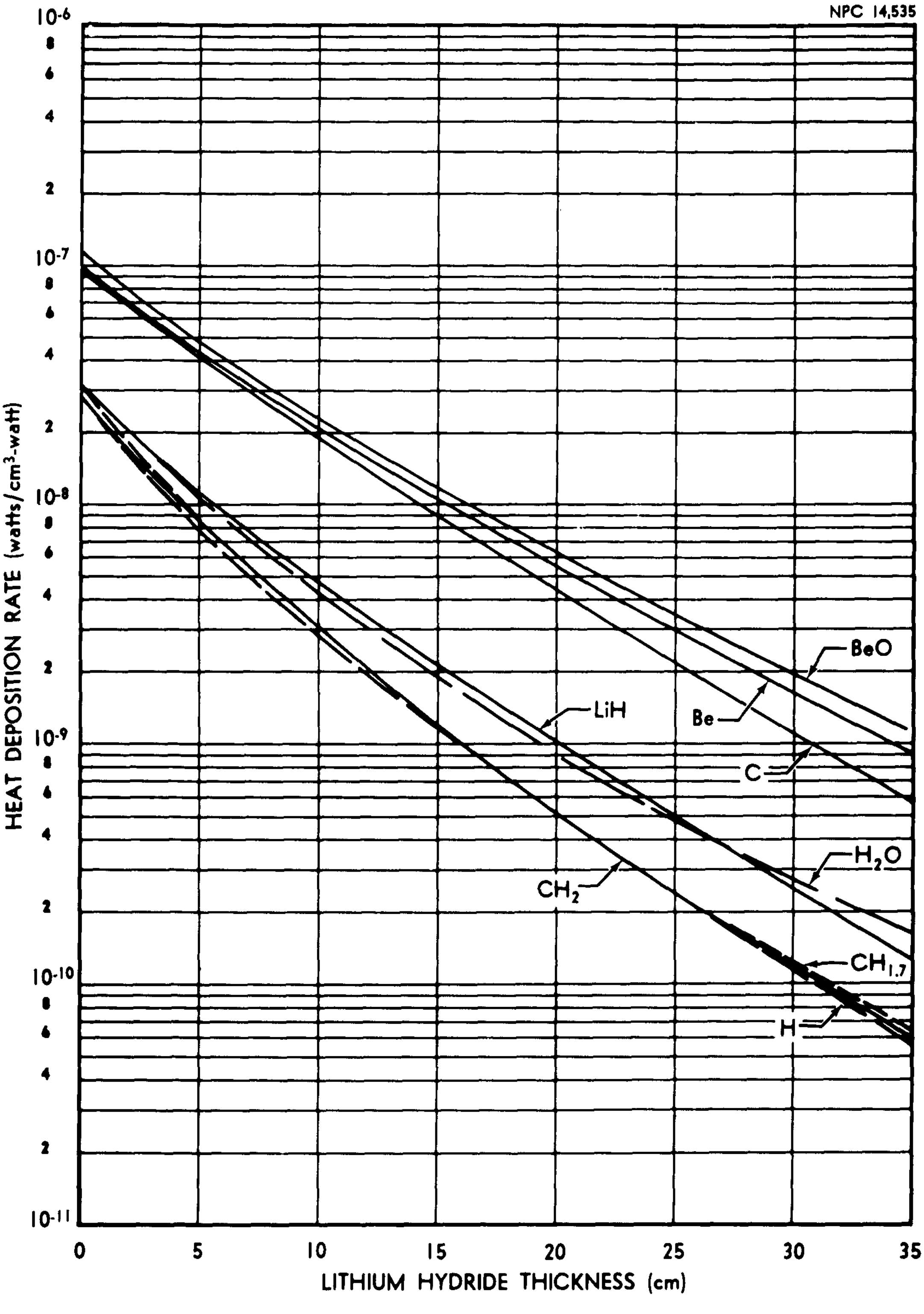


FIGURE C-1. HEAT DEPOSITION RATES IN LITHIUM HYDRIDE FOR VARIOUS BASE MATERIALS

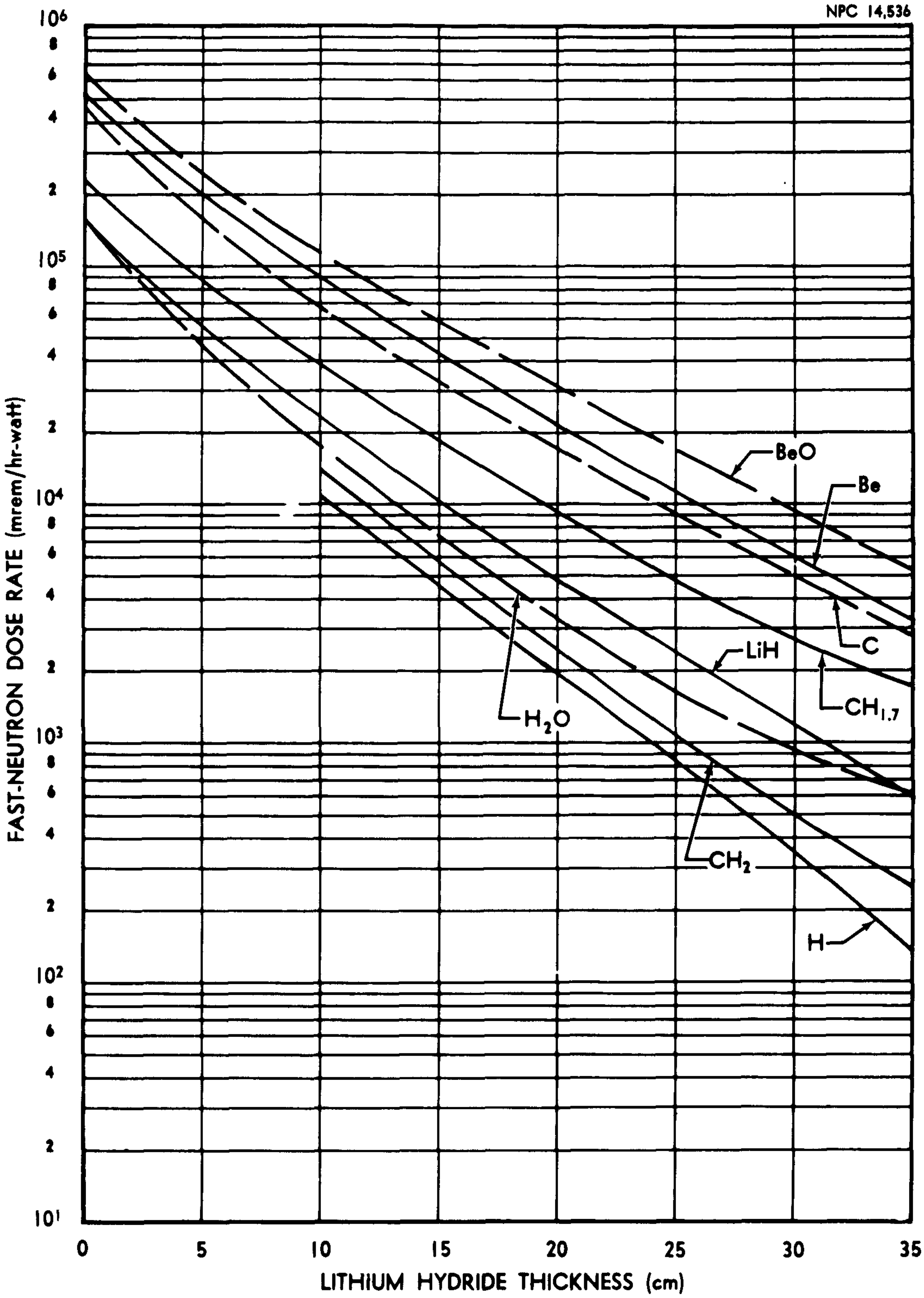


FIGURE C-2. FAST-NEUTRON DOSE RATES IN LITHIUM HYDRIDE FOR VARIOUS BASE MATERIALS

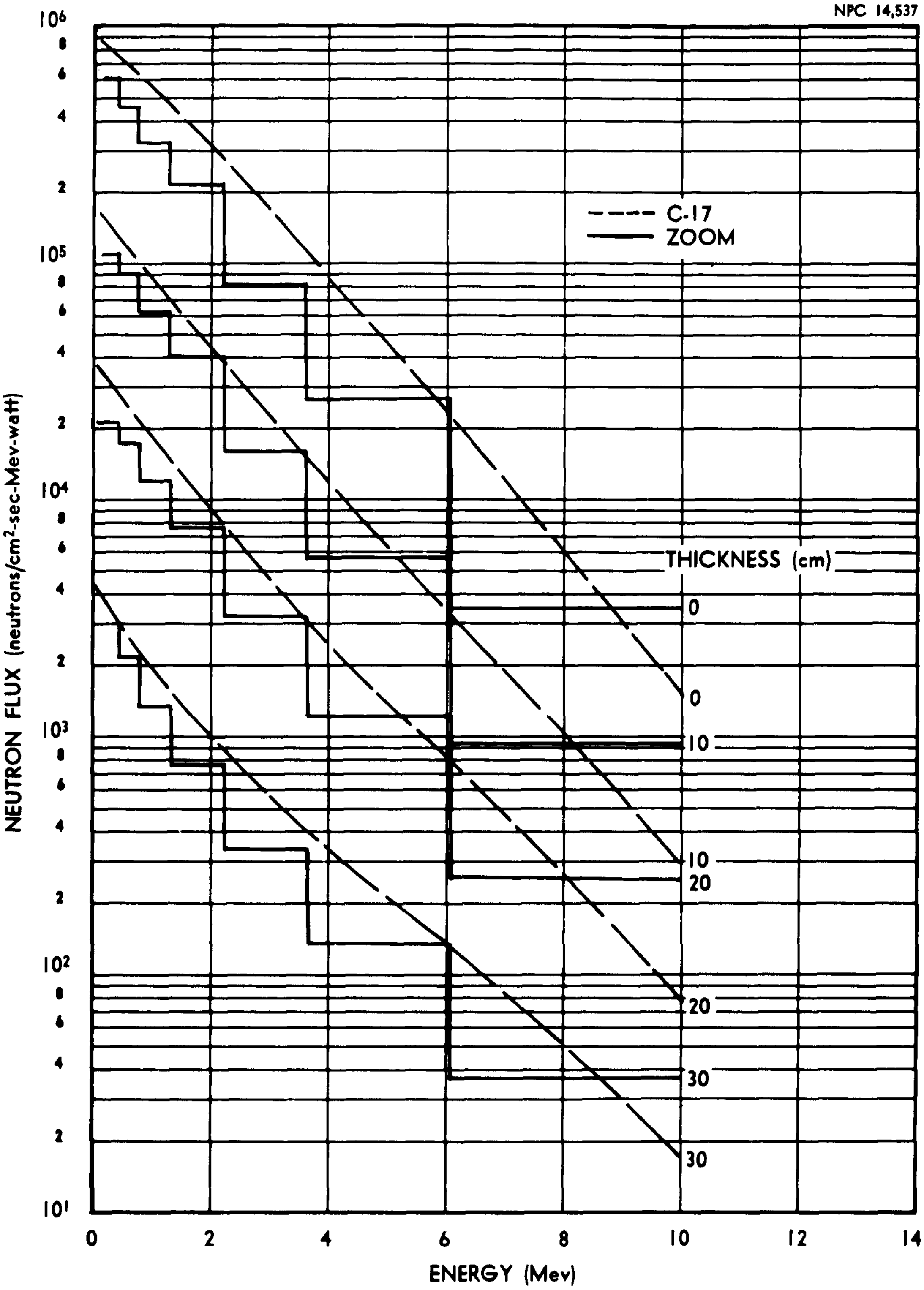


FIGURE C-3. COMPARISON OF C-17 AND ZOOM SPECTRA FOR LITHIUM HYDRIDE

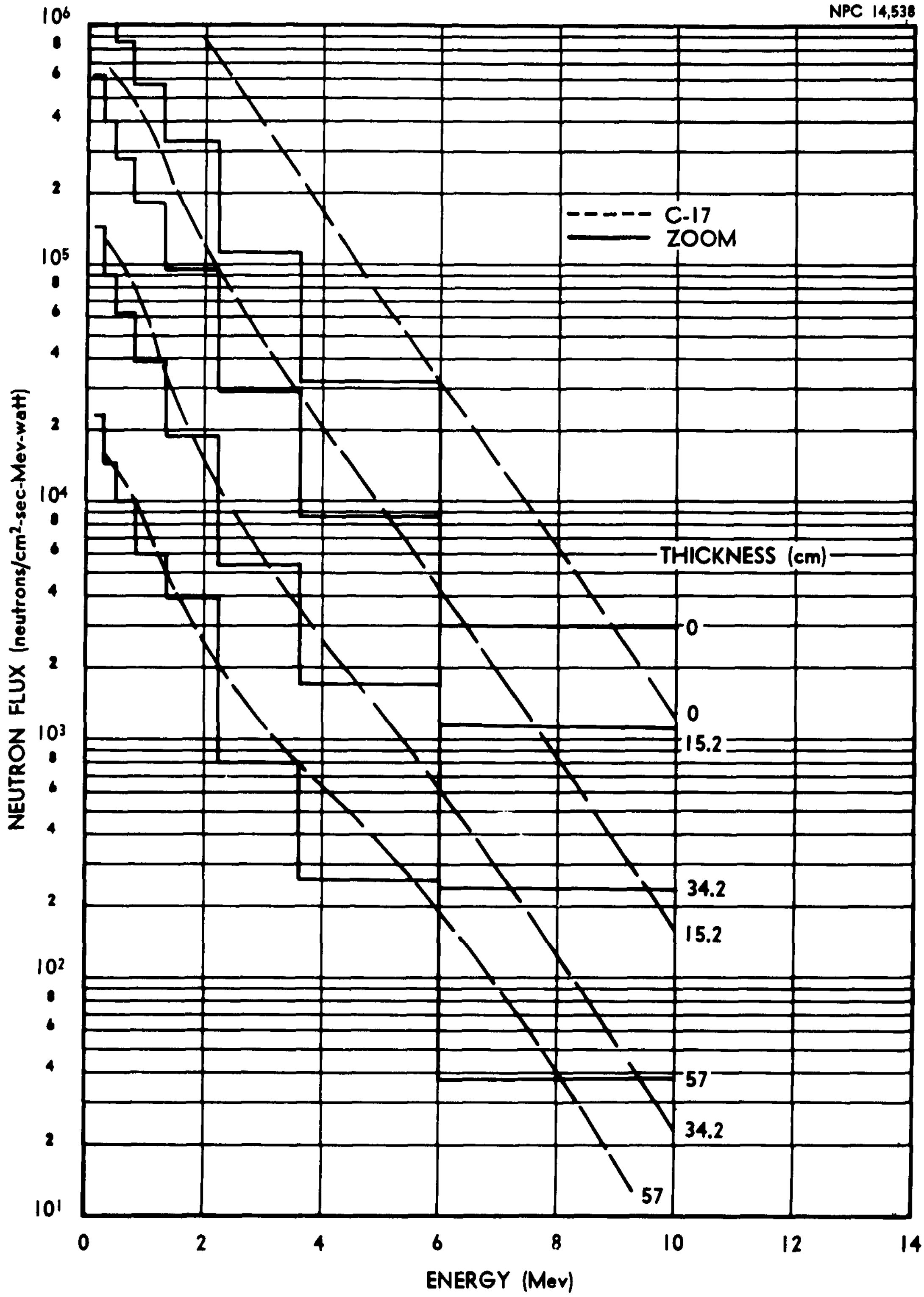


FIGURE C-4. COMPARISON OF C-17 AND ZOOM SPECTRA FOR BORATED CARBON

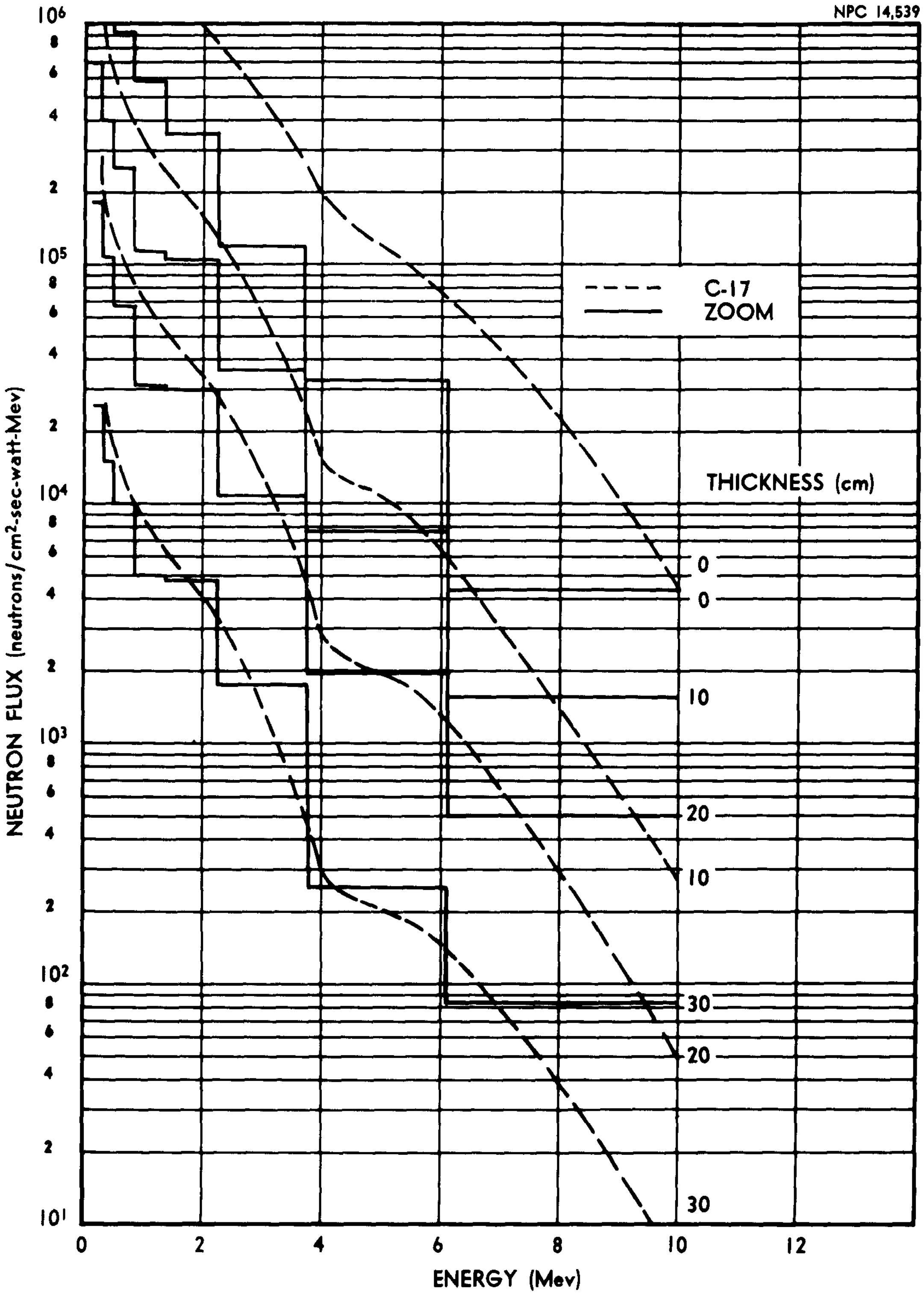


FIGURE C-5. COMPARISON OF C-17 AND ZOOM SPECTRA FOR BORATED BERYLLIUM OXIDE

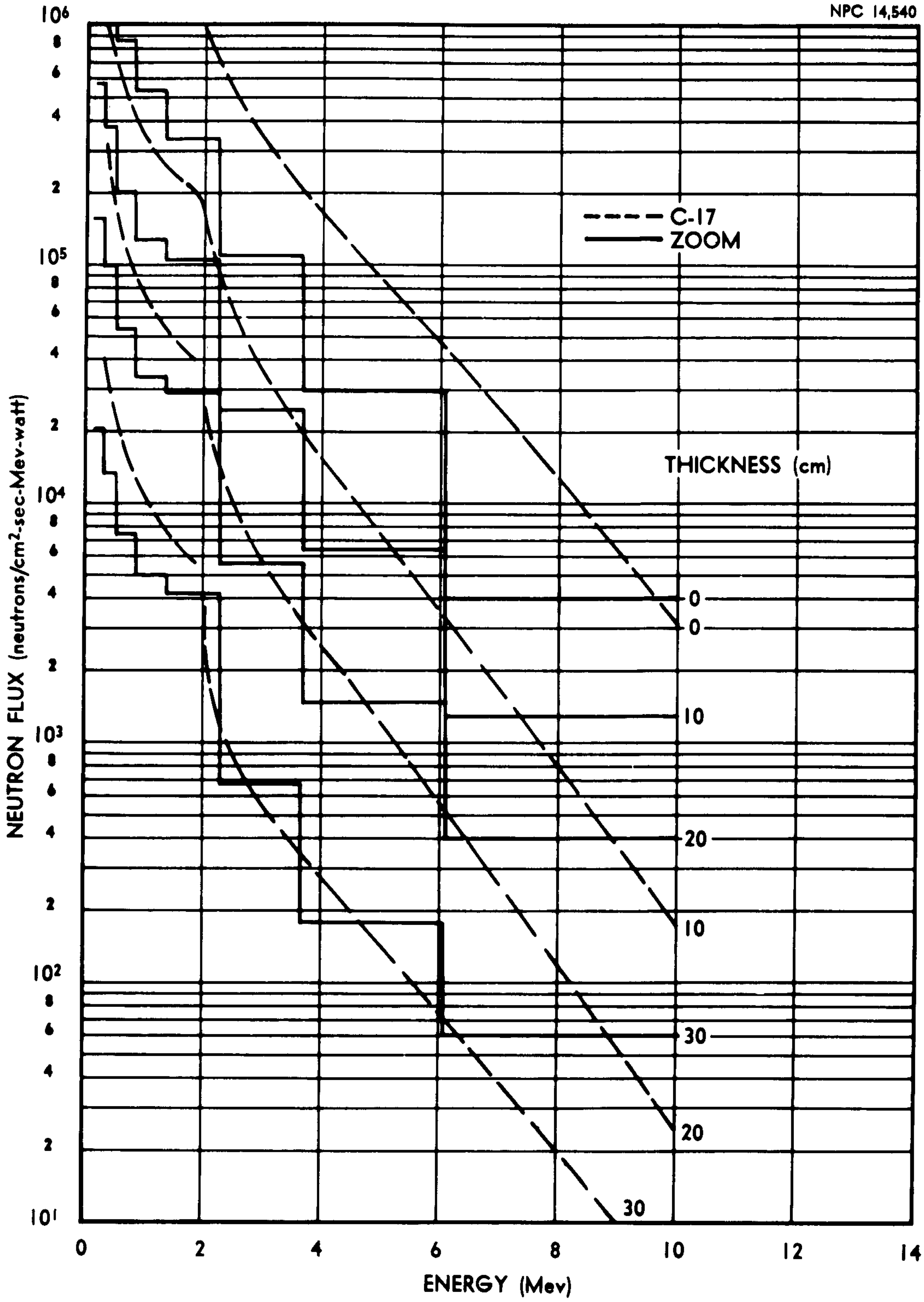


FIGURE C-6. COMPARISON OF C-17 AND ZOOM SPECTRA FOR BORATED BERYLLIUM

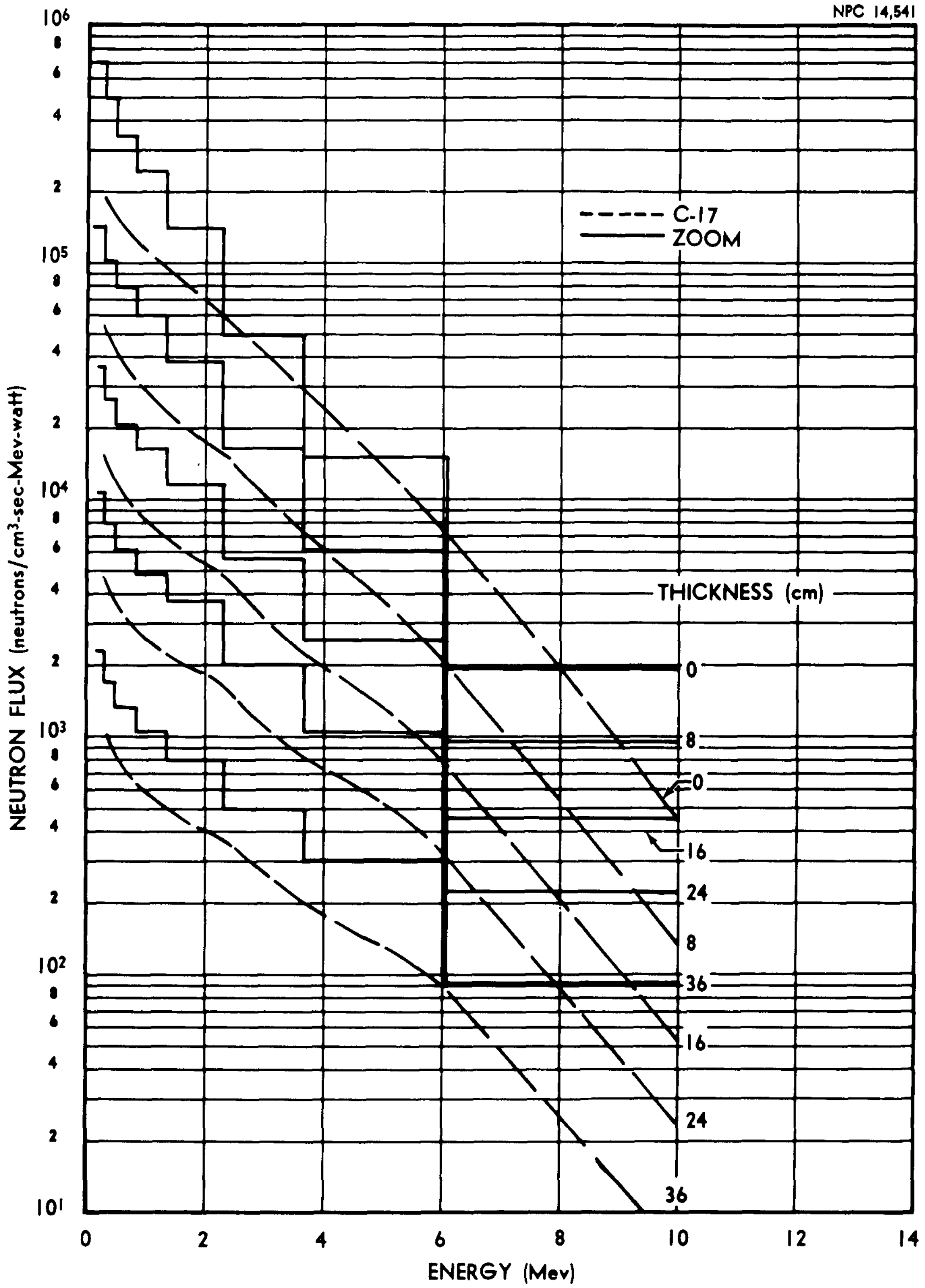


FIGURE C-7. COMPARISON OF C-17 AND ZOOM SPECTRA FOR BORATED POLYETHYLENE PLUS FIBER GLASS

APPENDIX D

PROGRAM LIBRARY DATA

The Library-Types 1 and 2 currently being used with programs C-17 and L-63 are presented in this appendix. The data are listed directly from the data cards; however, captions have been added to each Library-Type 1 material deck. The formats for the Library-Type 1 decks and the Library-Type 2 deck are shown in Figures 3-1 (Sec. 3.2) and 3-2 (Sec. 3.3), respectively.

LIBRARY-TYPE 1

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                                                               MODE 1


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8+2400-1+7+1 +2218-13+2560-1+7+1 +2018-13                         4813102004L   C17
8+2750-1+7+1 +1807-13+3010-1+7+1 +1586-13                         4813102005L   C17
8+3390-1+7+1 +1365-13+3960-1+7+1 +1120-13                         4813102006L   C17
8+4930-1+7+1 +8426-14+5970-1+7+1 +6300-14                         4813102007L   C17
8+7060-1+7+1 +4982-14+7980-1+7+1 +3750-14                         4813102008L   C17
8+9660-1+7+1 +2635-14+1263+0+7+1 +1250-14                    *12  4813102009L   C17
8+10+2 +411-12  +315-12  +132-12  +778-13  +565-13                4813102010L   C17
8       +461-13  +402-13  +336-13  +249-13  +157-13          *13  4813102011L   C17
6 +4  +4  +3  +2  +2  +1.5 +1  +1 +.825 +.565                *14  4813102012L   C17
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8-29524691-6+41082920-4-18763158-2-91046087-1-19700089+1          4813102019L   C17
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8-29905918-5+32728429-3-10450415-1-22630502-1-22300108+1          4813102023L   C17
6+60                                                              4813102024L   C17
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8+2400-1+7+1 +2218-13+2560-1+7+1 +2018-13                        4813103004L     C17
8+2750-1+7+1 +1807-13+3010-1+7+1 +1586-13                        4813103005L     C17
8+3390-1+7+1 +1365-13+3960-1+7+1 +1120-13                        4813103006L     C17
8+4930-1+7+1 +842[illegible]-14+5970-1+7+1 +6300-14              4813103007L     C17
8+7060-1+7+1 +4982-14+7980-1+7+1 +3750-14                        4813103008L     C17
8+9660-1+7+1 +2635-14+1263+0+7+1 +1250-14                   *12  4813103009L     C17
8+10+2 +411-12  +315-12  +132-12  +778-13  +565-13               4813103010L     C17
8      +461-13  +402-13  +336-13  +249-13  +157-13          *13  4813103011L     C17
6 +4.9 +4.1 +2.45 +1.19 +.61                                *14  4813103012L     C17
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8+27434048-6+10683361-5-17695110-2-[illegible]882759-1-10880081+1 4813103016L     C17
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LIBRARY-TYPE 1

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8+1920-1+3+1 +1086-13+2150-1+3+1 +9772-14                             4813104005L   C17
8+2460-1+3+1 +8458-14+2920-1+3+1 +6969-14                             4813104006L   C17
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LIBRARY-TYPE 1

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8+1610-1+3+1 +1205-13+1740-1+3+1 +1188-13                           4813105004L   C17
8+1920-1+3+1 +1086-13+2150-1+3+1 +0772-14                           4813105005L   C17
8+2460-1+3+1 +8458-14+2920-1+3+1 +6069-14                           4813105006L   C17
8+2600-1+3+1 +5158-14+4520-1+3+1 +3745-14                           4813105007L   C17
8+5300-1+3+1 +2755-14+5000-1+3+1 +1900-14                           4813105008L   C17
8+7260-1+3+1 +1103-14+9650-1+3+1 +4125-15                      *12  4813105009L   C17
8+10+2  +651-12   +114-12   +992-13   +646-13   +877-13             4813105010L   C17
8       +690-12   +582-13   +451-13   +2[illegible]-13   +205-13           *13  4813105011L   C17
6 +4.05 +4.05 +3.335 +2.22 +2.4 +.853 +.75 +.432               *14  4813105012L   C17
8-13817796-5+15706114-3-57224277-2+28160155-2-13730018+2            4813105013L   C17
8-13054738-5+15155910-3-49599400-2-54260626-1-87400023+1            4813105014L   C17
8-54809432-6+55111241-4-16241244-2-12551905-0-55710022+1            4813105015L   C17
8+23721321-6-26720430-4+81038754-3-17106771-0-35860032+1            4813105016L   C17
8+43753262-6-40265411-4+82128519-3-19283135-0-23719962+1            4813105017L   C17
8-57706012-6+85206575-4-43800469-2-10785121-0-12660027+1            4813105018L   C17
8-17081027-5+22100986-3-08043937-2-26745971-1-11030068+1            4813105019L   C17
8-26012137-5+33644096-3-14678305-1+52545641-1-11520183+1            4813105020L   C17
8-67787010-6+92343427-4-41058829-2-11359669-0-22300032+1            4813105021L   C17
6+60                                                                4813105022L   C17
8-31671280-8+17052734-5-31723757-3-57403296-1-13699907+2            4813105023L   C17
8+35047501-9-55102205-6+24341291-3-13508445-0-78566393+1            4813105024L   C17
8+25028416-6-21214888-5+67403384-3-19906068-0-42254571+1            4813105025L   C17
8+29108105-8-29004456-5+91145862-3-21861685-0-28714202+1            4813105026L   C17
8+28024345-8-23071830-5+68660220-3-20800521-0-28885190+1            4813105027L   C17
8+26095104-8-21305320-5+65528741-3-21222008-0-17567286+1            4813105028L   C17
8+35414315-9-27203297-5+77494117-3-22314484-0-10495509+1            4813105029L   C17
8+22673600-6-26780167-5+91560064-3-23058271-0-44491595-0            4813105030L   C17
8+36693714-7-17062846-4+31183202-2-24879708-0+76105438-2       *15  4813105031L   C17
```

LIBRARY-TYPE 1

MATERIAL 5 OIL ($CH_{1.7}$) NEUTRON ENERGY MODE 1

```
7LIBRARY DATA +1 +5  +1 +10                                          *10   4813106001L   C17
6+.111                                                               *11   4813106002L   C17
8+2100-1+5+1 +2467-13+2200-1+5+1 +2278-13                                  4813106003L   C17
8+2330-1+5+1 +2102-13+2500-1+5+1 +1917-13                                  4813106004L   C17
8+2700-1+5+1 +1720-13+2990-1+5+1 +1538-13                                  4813106005L   C17
8+3390-1+5+1 +1333-13+3980-1+5+1 +1096-13                                  4813106006L   C17
8+4990-1+5+1 +8330-14+6090-1+5+1 +6278-14                                  4813106007L   C17
8+7150-1+5+1 +4854-14+8120-1+5+1 +3666-14                                  4813106008L   C17
8+9790-1+5+1 +2523-14+1270+0+5+1 +1117-14                            *12   4813106009L   C17
8+10+2  +725-13   +700-13   +612-13   +604-13   +570-13                    4813106010L   C17
8       +512-13   +471-13   +388-13   +280-13   +179-13              *13   4813106011L   C17
6 +4  +4  +3  +2  +2  +1.5 +1  +1 +.825 +.565                        *14   4813106012L   C17
8-74502484-6+74727352-4-21707062-2-80017239-1-70600092+1                   4813106013L   C17
8-97036957-6+10159647-3-30692639-2-8949[illegible]-1-55000140+1            4813106014L   C17
8-22059105-5+21403808-3-56273071-2-82921[illegible]0-1-40000095+1          4813106015L   C17
8-31943441-6+37499018-4-12513542-2-13401702-0-26099994+1                   4813106016L   C17
8-19384372-5+20628775-3-63915054-2-92876449-1-19699991+1                   4813106017L   C17
8-79805241-6+09596250-4-39294953-2-11186128-0-14300109+1                   4813106018L   C17
8-22923963-5+26757677-3-96231606-2-46228928-1-10600137+1                   4813106019L   C17
8-45982625-5+54094374-3-20060345-1+10411500-0-11200237+1                   4813106020L   C17
8-25697770-5+29753572-3-10827513-1+30094173-1-22300092+1                   4813106021L   C17
6+60                                                                       4813106022L   C17
8+67103453-8-48587835-5+11090801-2-19967027-0-89696385+1                   4813106023L   C17
8+78176912-7-37454230-4+61496361-2-49782731-0-15174462-1                   4813106024L   C17
8+37446940-8-21905943-5+41697262-3-[illegible]3372551-0-62479256+1         4813106025L   C17
8+42639815-8-27301526-5+62055758-3-[illegible]6661407-0-42577630+1         4813106026L   C17
8-36988802-8+22003956-5-42497172-3-83367886-1-54933344+1                   4813106027L   C17
8-28764031-8+11461916-5-34964963-4-13420348-0-32831654+1                   4813106028L   C17
8-10555201-9-34141510-6+31069044-3-14957919-0-28192840+1                   4813106029L   C17
8+13406851-8-11895078-5+32407640-3-16565885-0-19966151+1                   4813106030L   C17
8+32927637-8-24321345-5+65556965-3-19006225-0-89398836+0                   4813106031L   C17
8+25678468-8-19532707-5+54549228-3-17861869-0-69777586+0                   4813106032L   C17
8+16544333-6-60100775-4+63605987-2-34837369-0+26350939-1             *15   4813106033L   C17
```

```
   MATERIAL  6      OIL (CH1.7)                        NEUTRON ENERGY
                                                          MODE 4
7LIBRARY DATA +1 +6  +4 +10                                          *10  4813107001L   C17
6+.111                                                               *11  4813107002L   C17
8+2100-1+5+1 +2467-13+2200-1+5+1 +2278-13                                 4813107003L   C17
8+2330-1+5+1 +2102-13+2500-1+5+1 +1917-13                                 4813107004L   C17
8+2700-1+5+1 +1720-13+2990-1+5+1 +1538-13                                 4813107005L   C17
8+3390-1+5+1 +1333-13+3980-1+5+1 +1096-13                                 4813107006L   C17
8+4990-1+5+1 +8330-14+6090-1+5+1 +6278-14                                 4813107007L   C17
8+7150-1+5+1 +4854-14+8120-1+5+1 +3666-14                                 4813107008L   C17
8+9790-1+5+1 +2523-14+1270+0+5+1 +1117-14                            *12  4813107009L   C17
8+10+2 +725-13   +700-13   +612-13   +604-13   +570-13                    4813107010L   C17
8        +512-13   +471-13   +388-13   +280-13   +179-13             *13  4813107011L   C17
6 +4.95+4.06+3.225+2.23+1.495+1.005+.67+.45+.385+.43                 *14  4813107012L   C17
8-10306574-5+10920202-3-32900544-2-86985186-1-55710102+1                  4813107013L   C17
8-62804715-6+65195054-4-20164181-2-10662550-0-35860049+1                  4813107014L   C17
8-72264270-6+74222 21-4-20162975-2-13743284-0-23720100+1                  4813107015L   C17
8-12359027-5+14001531-3-47657592-2-10430440-0-16610098+1                  4813107016L   C17
8-13[illegible]062-5+15600364-3-54532024-2-99114761-1-12660031+1          4813107017L   C17
8-1[illegible]1-[illegible]167-3-20564613-2-65600206-1-10790168+1         4813107018L   C17
8-2[illegible]-5+[illegible]679-3-11644163-1-16993312-1-10270183+1        4813107019L   C17
8-[illegible]1037-5+5427[illegible]15-3-20[illegible]2522-1+11072368-0-11520213+1   4813107020L   C1[illegible]
8-[illegible]051-[illegible]1031-3-12633881-1+56596741-1-23540115+1       4813107021L   C17
[illegible]                                                               4813107022L   C17
[illegible]-[illegible]825-5+1[illegible]-2-19967027-0-89696385+1         4813107023L   C17
[illegible]-[illegible]-5+50086965-3-13630785-0-74121340+1                4813107024L   C17
[illegible]47-[illegible]-5+[illegible]-3-15771710-0-46222626+1           4813107025L   C17
[illegible]-15[illegible]-5+47209758-3-17130153-0-24109549+1              4813107026L   C17
8-[illegible]-5+17513660-5-17004143-3-12184850-0-36187750+1               4813107027L   C17
8+1[illegible]-[illegible]-5+4[illegible]80173-3-17033271-0-19267081+1    4813107028L   C17
8+1[illegible]-[illegible]-16[illegible]375-5+49948008-3-17583330-0-15981607+1   4813107029L   C17
8+1[illegible]528-[illegible]-15764369-5+49752800-3-17633754-0-13591142+1  4813107030L   C17
[illegible]-[illegible]-1793191[illegible]-5+5[illegible]61031-3-17800696-0-11210446+1   4813107031L   [illegible]7
8+21304742-[illegible]-174[illegible]610-5+5[illegible]53301-3-17864883-0-64396581+0   4813107032L   C17
8+1652967[illegible]-[illegible]-600[illegible]615[illegible]-4+63514916-2-24706416-0+26349956-1  *15  4813107033L   C17
```

LIBRARY-TYPE 1

```
MATERIAL  7      BERYLLIUM                         NEUTRON ENERGY
                                                       MODE 1

7LIBRARY DATA +1 +7  +1 +10                               *10  4813108001L   C17
6+.0717                                                   *11  4813108002L   C17
8+1610-1+4+1 +1800-13+1620-1+4+1 +1745-12                      4813108003L   C17
8+1800-1+4+1 +1628-13+1940-1+4+1 +150[illegible]-12            4813108004L   C17
8+2110-1+4+1 +1365-13+2240-1+4+1 +1212-12                      4813108005L   C17
8+2660-1+4+1 +1057-13+3130-1+4+1 +[illegible]-12               4813108006L   C17
8+2940-1+4+1 +6728-14+4760-1+4+1 +[illegible]-12               4813108007L   C17
8+5650-1+4+1 +3080-14+6[illegible]0-1+4+1 +2141-12             4813108008L   C17
8+7730-1+4+1 +2115-14+9830-1+4+1 +[illegible]-12          *12  4813108009L   C17
8+10+2 +149-12  +117-12  +767-13  +6[illegible]-13  +407-13    4813108010L   C17
8       +301-13  +247-13  +924-14  +50[illegible]-14  +[illegible]-14  *13  4813108011L   C17
6 +4  +4  +3  +2  +2  +1.5 +1  +1 +.825 +.565             *14  4813108012L   C17
8 +32062087-6 -32667[illegible]-1 +1[illegible]-0 -[illegible]270416+1 -15222165+1 4813108013L   C17
8 +23427529-4 -2[illegible]-1 +1[illegible]-0 -[illegible]+1 -11466521+1 4813108014L   C17
8 +15461577-4 -1[illegible]750[illegible]-1 +[illegible]-1 -1[illegible]40[illegible]+1 -[illegible]66[illegible]50+0 4813108015L   C17
8 +11645891-4 -141723[illegible]4-2 +[illegible]6817[illegible]-1 -266101117+0 -60999767+0 4813108016L   C17
8 +789[illegible]6476-5 -46 26066-2 +[illegible]-1 -[illegible]+0 -64221746+0 4813108017L   C17
8 +49510072-5 -60[illegible]-2 +[illegible]-1 -[illegible]+0 -28[illegible]7+0 4813108018L   C17
8 +37610699-5 -44[illegible]-2 +[illegible]-1 -[illegible]-0 -2222 026+0 4813108019L   C17
8 +26639742-5 -2081760[illegible]-2 +[illegible]-1 -14[illegible]-0 -1[illegible]-0 4813108020L   C17
8 +11280055-5 -11796[illegible]-2 +30[illegible]-2 -[illegible]71016-1 -11[illegible]-0 4813108021L   C17
8 -1[illegible]13697-5 +24752429-2 -11[illegible]-1 +1[illegible]60[illegible]75+0 -1[illegible]+0 4813108022L   C17
8 +33628660-5 -29718300-3 +14[illegible]1[illegible]-1 -26[illegible]3803+0 -2[illegible]634+0 4813108023L   C17
6+60                                                           4813108024L   C17
8 +87659802-7 -42283065-4 +7[illegible]1641-1 -58262221+0 -70764125-2 4813108025L   C17
8 +63081849-7 -20621[illegible]-4 +5[illegible]-2 -44[illegible]-0 -68705276-3 4813108026L   C17
8 -21680241-9 +13[illegible]5721-6 -2[illegible]-5 -6[illegible]14230[illegible]-1 -6635[illegible]79+1 4813108027L   C17
8 -17[illegible]3242-9 +10716[illegible]48-6 -1[illegible]1-4 -6[illegible]12742-1 -5[illegible]+1 4813108028L   C17
8 +23110611-7 -10[illegible]0-4 +1[illegible]327-2 -[illegible]5200[illegible]+0 -[illegible]576001-2 4813108029L   C17
8 +12506261-7 -5[illegible]-6 +1[illegible]-2 -1[illegible]+0 -12317225-2 4813108030L   C17
8 -76701899-9 +42982776-6 -[illegible]-4 -7[illegible]369-1 -1[illegible]601+1 4813108031L   C17
8 +50629279-9 +5512[illegible]5-6 -2[illegible]-2 -5[illegible]1[illegible]08-1 -5[illegible]2-4 4813108032L   C17
8 -46847179-9 +47424[illegible]7-6 -1[illegible]27-2 -61767000-1 +6[illegible]01[illegible]+0 4813108033L   C17
8 -30090962-9 +22691[illegible]44-5 -6098[illegible]-2 -1[illegible]-1 +4720[illegible]-2 4813108034L   C17
8 +51257950-9 -2[illegible]-6 +[illegible]-4 -95200622-1 -1[illegible]72535-2 4813108035L   C17
:                                                         *15  4813108036L   C17
```

LIBRARY-TYPE 1

```
MATERIAL   8      BERYLLIUM +                        NEUTRON ENERGY
                  .01 BORON (BY WEIGHT)                MODE 4

7LIBRARY DATA +1 +8  +4 +10                                            *10  48131090011L   C17
6+.0717                                                                *11  48131090021L   C17
8+1610-1+4+1 +1890-13+1690-1+4+1 +1745-13                                   48131090031L   C17
8+1800-1+4+1 +1628-13+1940-1+4+1 +1502-13                                   48131090041L   C17
8+2110-1+4+1 +1355-13+2340-1+4+1 +1218-13                                   48131090051L   C17
8+2660-1+4+1 +1057-13+3130-1+4+1 +8795-14                                   48131090061L   C17
8+3940-1+4+1 +6728-14+4760-1+4+1 +5023-14                                   48131090071L   C17
8+5650-1+4+1 +3989-14+6520-1+4+1 +3161-14                                   48131090081L   C17
8+7720-1+4+1 +2115-14+9820-1+4+1 +8931-15                              *12  48131090091L   C17
8+10+2 +149-12  +117-12  +747-13  +685-13  +497-13                          48131090101L   C17
8       +301-13  +247-13  +824-14  +509-14  +286-14                    *13  48131090111L   C17
6 +4.95+4.96+3.325+2.23+1.495+1.005+.67+.45+.385+.43                   *14  48131090121L   C17
8+78097806-10-23472440-7 -17788203-4 -50820939-1 -13688321+2                48131090131L   C17
8-24522417-6 +21027203-6 -72714349-4 -52732047-1 -86821915+1                48131090141L   C17
8-63042449-9 +40225944-6 -12091026-3 -58010280-1 -55036167+1                48131090151L   C17
8-11881449-3 +82640406-6 -19773926-3 -59259867-1 -35054293+1                48131090161L   C17
8+41540432-5 -51199775-2 +20834704-1 -40829022+0 -26354552+0                48131090171L   C17
8+02227405-2 -26757502-3 +10221707-1 -22018657+0 -18452455+0                48131090181L   C17
8+00380738-6 -10550302-3 +35610955-2 -89774368-1 -14064984+0                48131090191L   C17
8+51408765-6 -32525065-4 +11977722-2 -47240963-1 -11986758+0                48131090201L   C17
8-45[illegible]-6 +90824[illegible]-4 -44606681-2 +44678463-1 -11413643+0   48131090211L   C17
8-12213697-2 +2475[illegible]-3 -11405302-2 +16960575+0 -12800295+0         48131090221L   C17
8+33679660-2 -39718[illegible]-3 +1492915[illegible] -26483803+0 -24697634+0 48131090231L  C17
6+60                                                                        48131090241L   C17
8+78097806-10-23472440-7 -17788203-4 -50820939-1 -13688321+2                48131090251L   C17
8-24522717-3 +21037203-6 -72714349-4 -52732047-1 -86821915+1                48131090261L   C17
8-63342449-3 +40225944-6 -12091026-3 -58010280-1 -55036167+1                48131090271L   C17
8-11971449-2 +82640406-6 -12773926-3 -59259867-1 -35054293+1                48131090281L   C17
8+17557277-4 -12326718-5 +40397742-3 -12666179+0 -32713211-2                48131090291L   C17
8-22049818-3 +34096668-7 +50225004-4 -93864196-1 +24404772-3                48131090301L   C17
8-90756763-9 +77128925-6 -22253440-3 -51101205-1 +61749351-3                48131090311L   C17
8-13850805-8 +10841113-5 -30369480-3 -44839080-1 +15212320-2                48131090321L   C17
8-19827059-8 +15228278-5 -41531146-3 -33447814-1 +25765767-2                48131090331L   C17
8-20000962-8 +22681544-5 -60985671-3 -12605918-1 +47205570-2                48131090341L   C17
8+51257959-9 -22127719-6 +71740404-4 -85300698-1 -13872585-2                48131090351L   C17
6                                                                      *15  48131090361L   C17
```

LIBRARY-TYPE 1

MATERIAL 9 BERYLLIUM OXIDE NEUTRON ENERGY MODE 1

```
7LIBRARY DATA +1 +0  +1 +10                                              *10  4813110001L   C17
6+.0407                                                                  *11  4813110002L   C17
8+1560-1+7+1 +1746-13+1750-1+7+1 +1726-13                                     4813110003L   C17
8+1950-1+7+1 +1756-13+2160-1+7+1 +1682-13                                     4813110004L   C17
8+2390-1+7+1 +1567-13+2610-1+7+1 +1370-13                                     4813110005L   C17
8+2940-1+7+1 +1179-13+3420-1+7+1 +9612-14                                     4813110006L   C17
8+4270-1+7+1 +7273-14+5120-1+7+1 +5209-14                                     4813110007L   C17
8+6100-1+7+1 +4245-14+7020-1+7+1 +3242-14                                     4813110008L   C17
8+9250-1+7+1 +2235-14+1030+0+7+1 +8010-15                                *12  4813110009L   C17
8+10+2 +312-13  +220-13  +350-13  +456-13  +252-13                            4813110010L   C17
8      +181-13  +158-13  +450-14  +327-14  +165-14                       *13  4813110011L   C17
6 +4  +4  +3  +2  +2  +1.5 +1  +1 +.825 +.565                            *14  4813110012L   C17
9 +37006315-5 -74096613-2 +50065571-1 -12859192+1 -17124994+1 4813110013L   C17
8 +15401137-5 -34599121-2 +27109296-1 -91817476+0 -12997622+1 4813110014L   C17
8 +21034971-5 -41571431-3 +27432009-1 -74777138+0 -86124784+0 4813110015L   C17
8 +12816606-5 -25305[illegible]24-4 +17762977-1 -52659963+0 -68749949+0 4813110016L   C17
8 +94221070-6 -15974209-2 +[illegible]-1 -18707775+0 -49624952+0 4813110017L   C17
8 +52478009-6 -10629[illegible]-3 +[illegible]7747-2 -24596425+0 -32500045+0 4813110018L   C17
8 +30674777-6 -7451[illegible]76-4 +51054503-2 -16887951+0 -24999982+0 4813110019L   C17
8 +22017513-6 -41969055-4 +25115942-2 -92144473-1 -18124968+0 4813110020L   C17
9 +41919095-7 -56845966-5 -17222246-4 -21214029-1 -13125029+0 4813110021L   C17
8 -22203727-6 +62649311-4 -52021222-2 +12346509+0 -14400173+0 4813110022L   C17
9 +24338033-6 -66506293-4 +41518698-2 -12764661+0 -27794095+0 4813110023L   C17
6+20                                                                          4813110024L   C17
9 +32101455-7 -42572290-4 +73427367-2 -58435218+0 -62102209-3 4813110025L   C17
8 +11227947-6 -51526305-4 +90796626-2 -54748343+0 +40527154-2 4813110026L   C17
8 +22165701-7 -18566601-4 +23543963-2 -29924875-0 -46254097-3 4813110027L   C17
8 -69219366-9 +56973280-6 -18374590-3 -20666435-1 -58508575+1 4813110028L   C17
8 +23899551-7 -11302965-4 +12852294-2 -17301219-0 -34231946-3 4813110029L   C17
9 +19820390-7 -55041[illegible]95-5 +16418262-2 -14870797-0 +92064397-4 4813110030L   C17
8 +66580760-9 -22158321-5 +56371130-2 -95066183-1 -26251718-2 4813110031L   C17
8 -21492112-9 +37558342-6 -98064404-4 -36543189-1 -38672737-0 4813110032L   C17
8 -47593862-9 +21047001-5 -51423716-2 -14121218-1 -40114095-3 4813110033L   C17
9 -17726982-9 +13152482-6 -25064774-3 -41319930-1 +14591924-2 4813110033L   C17
8 -20079973-9 +15902306-5 -45514942-3 +27584365-2 +58834930-3 4813110034L   C17
9 +43242726-9 -22146222-5 +77121099-4 -58736612-1 -16150771-3 4813110035L   C17
6                                                                        *15  4813110036L   C17
```

LIBRARY-TYPE 1

```
   MATERIAL 10      BERYLLIUM OXIDE +          NEUTRON ENERGY
                     .01 BORON (BY WEIGHT)        MODE 4

7LIBRARY DATA +1 +10 +4 +10                                          *10  4813111001L   C17
6+.0497                                                              *11  4813111002L   C17
8+1560-1+7+1 +1746-13+1750-1+7+1 +1726-13                                 4813111003L   C17
8+1950-1+7+1 +1756-13+2160-1+7+1 +1682-13                                 4813111004L   C17
8+2390-1+7+1 +1567-13+2610-1+7+1 +1370-13                                 4813111005L   C17
8+2940-1+7+1 +1179-13+3420-1+7+1 +9612-14                                 4813111006L   C17
8+4270-1+7+1 +7273-14+5120-1+7+1 +5200-14                                 4813111007L   C17
8+6100-1+7+1 +4245-14+7020-1+7+1 +3342-14                                 4813111008L   C17
8+8350-1+7+1 +2235-14+1030+0+7+1 +8010-15                            *12  4813111009L   C17
8+10+2 +308-12  +227-12  +857-13  +462-13  +257-13                        4813111010L   C17
8      +183-13  +158-13  +455-14  +329-14  +166-14                   *13  4813111011L   C17
6 +4.95+4.96+3.325+2.23+1.495+1.005+.67+.45+.385+.43                 *14  4813111012L   C17
8+38989201-10-55940745-8 -15954429-4 -49342141-1 -13743292+2              4813111013L   C17
8+66195906-5 -11964279-2 +67639881-1 -13542679+1 -10925229+1              4813111014L   C17
8-31505301-9 +26424436-6 -23872135-4 -31297849-1 -55155854+1              4813111015L   C17
8-10016221-8 +77140982-6 -21284366-3 -27020790-1 -35491297+1              4813111016L   C17
8-46287263-9 +33117047-6 -84459738-4 -42982584-1 -23443755+1              4813111017L   C17
8+26211447-6 -51035696-4 +31541257-2 -10830759+0 -20752103+0              4813111018L   C17
8+11640455-6 -23072293-4 +14325779-2 -71163199-1 -15823114+0              4813111019L   C17
8+27312113-7 -36329727-5 -67451852-4 -23466201-1 -13485125+0              4813111020L   C17
8-20025979-6 +42421967-4 -32171016-2 +60162087-1 -12840290+0              4813111021L   C17
8-32293737-6 +68649311-4 -52021122-2 +12346508+0 -14400173+0              4813111022L   C17
8+34230832-6 -66586383-4 +41815635-2 -13763661+0 -27784995+0              4813111023L   C17
6+90                                                                      4813111024L   C17
8+38989201-10-55940745-8 -15954429-4 -49342141-1 -13743292+2              4813111025L   C17
8+77780637-8 -61366270-5 +17150785-2 -25305479+0 -23510073-2              4813111026L   C17
8-31505301-9 +26424436-6 -23872135-4 -31287849-1 -55155854+1              4813111027L   C17
8-10016221-8 +77140982-6 -21284366-3 -27020790-1 -35491297+1              4813111028L   C17
8-46287262-9 +33117047-6 -84459738-4 -42982584-1 -23443755+1              4813111029L   C17
8+31104924-10+14172400-7 -22643071-4 -47093852-1 -93421183-4              4813111030L   C17
8-56941091-10+82008228-7 -45342393-4 -42535348-1 -28396505-4              4813111031L   C17
8-59094493-9 +49734871-6 -15896729-3 -29939155-1 +15217458-3              4813111032L   C17
8-12315732-8 +10015402-5 -29981659-3 -13628579-1 +34486132-3              4813111033L   C17
8-20079972-8 +15992395-5 -45914942-3 +37594365-2 +58834920-3              4813111034L   C17
8+43243736-9 -32145232-6 +77121099-4 -58736613-1 -16150771-3              4813111035L   C17
6                                                                    *15  4813111036L   C17
                                                                            000040
```

LIBRARY-TYPE 1

```
     MATERIAL 11       HYDROGEN                          NEUTRON ENERGY
                                                              MODE 1
7LIBRARY DATA +1 +11 +1 +10                                         *10  4813112001L     C17
6+.672                                                              *11  4813112002L     C17
8        +321-1    +1+1 +250-14   +344-1    +1+1   +390-14               4813112003L     C17
8        +371-1    +1+1 +402-14   +405-1    +1+1   +432-14               4813112004L     C17
8        +446-1    +1+1 +465-14   +502-1    +1+1   +505-14               4813112005L     C17
9        +579-1    +1+1 +566-14   +601-1    +1+1   +622-14               4813112006L     C17
8        +976-1    +1+1 +743-14   +107+0    +1+1   +825-14               4813112007L     C17
9        +126+0    +1+1 +882-14   +145+0    +1+1   +918-14               4813112008L     C17
8        +173+0    +1+1 +942-14   +224+0    +1+1   +864-14          *12  4813112009L     C17
9+10+2 +469-12   +436-12   +449-12   +426-12   +414-12                   4813112010L     C17
8         +350-12   +332-12   +291-12   +205-12   +123-12           *13  4813112011L     C17
6 +4   +4   +3   +2   +2   +1.5 +1   +1 +.825 +.565                 *14  4813112012L     C17
8 -15826844-2 +33012191-1 -21879494-0 +14318371-0 -13724462+2 4813112013L     C17
9 +10655547-0 -14171534+1 +61455690+1 -10801003+2 -43701751+1 4813112014L     C17
8 +75070566-1 -10046126+1 +43076507+1 -20061893+1 -27856189+1 4813112015L     C17
9 +66006225-1 -87858660+0 +28182746+1 -70947976+1 -17921059+1 4813112016L     C17
9 +50625730-1 -67231685+0 +22228082+1 -56901650+1 -11860803+1 4813112017L     C17
9 +31785607-2 -56818289-1 +46766995-0 -20437682+1 -16792805+1 4813112018L     C17
8 +20680246-1 -32441652-0 +16100377+1 -25167961+1 -63304802+0 4813112019L     C17
9 +11230490-2 -22411211-1 +16190701-0 -13872072+1 -10829480+1 4813112020L     C17
9 -80560520-3 +20560011-1 -11222243-0 -43809365+0 -10245570+1 4813112021L     C17
9 -17450425-2 +41719719-1 -21524122-0 -59272902-1 -11417117+1 4813112022L     C17
5 -97477697-3 +20125557-1 -11162221+0 -71690980 -22220793+1   4813112023L     C17
6+5.66                                                               4813112024L     C17
8 +61705030-5 -65290014-3 +22661008-1 -61962479+0 -12581522+2 4813112025L     C17
9 -66074822-6 +51122917-4 -12159471-2 -37104213+0 -10201750+2 4813112026L     C17
9 -93200279-6 +10155082-3 -23122290-2 -44592834+0 -70820851+1 4813112027L     C17
9 +56618229-5 -50253050-2 +22062121-1 -87915510+0 -43848610+1 4813112028L     C17
9 +26121605-6 -21152422-3 +10025515-1 -91720404+0 -31825612+1 4813112029L     C17
9 -27458716-6 -11175692-3 +12742062-1 -92141471+0 -24527426+1 4813112030L     C17
5 +21186041-5 -40520867-3 +23210156-1 -10524115+1 -17195359+1 4813112031L     C17
9 +13200802-5 -25102057-2 +17201640-1 -96776942+0 -18007708+1 4813112032L     C17
9 +14314967-3 -63624906-4 +11126199+0 -15871982+1 -25771045-4 4813112033L     C17
9 -28166816-5 +80175010-4 +20297046-4 -99209976+0 -12018011+1 4813112034L     C17
9 +20534187-6 -27586742-2 +12042210-1 -10215114+1 -20267404+1 4813112035L     C17
6                                                                   *15  4813112036L     C17
```

LIBRARY-TYPE 1

```
    MATERIAL 12      HYDROGEN                         NEUTRON ENERGY
                                                          MODE 4
7LIBRARY DATA +1 +12 +3 +8[illegible]                            #10  4813113001L   C17
64.67[illegible]                                                 #11  4813113002L   C17
9     +321-1  +1+1 +360-14  +344-1  +1+1  +380-14             4813113003L   C17
9     +371-1  +1+1 +407-14  +405-1  +1+1  +432-14             4813113004L   C17
9     +444-1  +1+1 +448-14  +[illegible]-1  +1+1  +508-14             4813113005L   C17
9     +570-1  +1+1 +566-14  +601-1  +1+1  +620-14             4813113006L   C17
9     +276-1  +1+1 +742-14  +107+0  +1+1  +[illegible]-14             4813113007L   C17
9     +126+0  +1+1 +882-14  +145+0  +1+1  +913-14             4813113008L   C17
9     +172+0  +1+1 +942-14  +224+0  +1+1  +854-14        #12  4813113009L   C17
8+10+2 +459-12  +486-12  +448-12  +436-12  +414-12            4813113010L   C17
8       +350-12  +332-12  +231-12  +205-12  +133-12      #13  4813113011L   C17
6 +4.25+4.06+2.35+2.22+1.495+1.005+.674+.45+.385+.42     #14  4813113012L   C17
8 -15660204-2 +32746101-1 -21791766-0 +14244597-0 -13724690+2 4813113013L   C17
8 +22611679-2 -63209756-1 +76201660-0 -15727101+1 -97540426+1 4813113014L   C17
8 +70158271-1 -92496422+0 +40682270+1 -74709109+1 -22901105+1 4813113015L   C17
8 +50525730-1 -67221680+0 +79228082+1 -56901650+1 -11860803+1 4813113016L   C17
8 +29141607-2 -59920560-1 +41210822-0 -10116026+1 -16752202+1 4813113017L   C17
8 +05211229-2 -30205467-2 +27121076-1 -11067523+1 -10450035+1 4813113018L   C17
8 -70[illegible]0162-2 +10186662-1 -1[illegible]09[illegible]74-0 -56232160+0 -10570539+1 4813113019L   C17
8 -17[illegible]-2 +[illegible]19-1 -[illegible]-0 -[illegible]37[illegible]0[illegible]-1 -11417117+1 4813113020L   C17
8 -[illegible]74[illegible]7607-2 +90[illegible]7-1 -1[illegible]16[illegible]1+0 -71[illegible]0[illegible]+0 -22220792+1 4813113021L   C17
6 .46.66                                                      4813113022L   C17
9 +61[illegible]-5 -65[illegible]0014-2 +22662002-1 -61962679+0 -12581522+2 4813113023L   C17
8 -[illegible]-5 +[illegible]-2 -6[illegible]10-2 -32714704+0 -92067719+1 4813113024L   C17
9 +41209614-5 -42110967-2 +16[illegible]07-1 -72202625+0 -55212626+1 4813113025L   C17
8 +20121625-5 -21152433-2 +19[illegible]615-1 -21790604+0 -31835612+1 4813113026L   C17
9 +27229640-6 -17292722-1 +16711222-1 -94610527+0 -22211684+1 4813113027L   C17
9 +14248218-5 -26090 [illegible]-2 +17420120-1 -96146272+0 -17115804+1 4813113028L   C17
9 -20240610-6 -72007069-4 +12225601-1 -[illegible]21[illegible]7676+0 -15002414+1 4813113029L   C17
9 -22166914-5 +20175010-4 +82927946-2 -99269276+0 -12019011+1 4813113030L   C17
9 +55524187-6 -27536462-2 +2290[illegible]310-1 -10215114+1 -20267404+1 4813113031L   C17
6                                                        #15  4813113032L   C17
```

MATERIAL 13 POLYETHYLENE (CH_2) NEUTRON ENERGY
MODE 1

```
7LIBRARY DATA +1 +13 +1 +10                                              *10  4813114001L   C17
64.1101                                                                  *11  4813114002L   C17
8+706-1 +5+1 +2419-13  +213-1 +5+1 +2102-13                                   4813114003L   C17
9+220-1 +5+1 +2061-13  +246-1 +5+1 +1382-13                                   4813114004L   C17
9+266-1 +5+1 +1701-13  +294-1 +5+1 +1506-13                                   4813114005L   C17
8+322-1 +5+1 +1301-13  +392-1 +5+1 +1091-13                                   4813114006L   C17
8+492-1 +5+1 +8202-14  +606-1 +5+1 +6279-14                                   4813114007L   C17
9+705-1 +5+1 +4790-14  +802-1 +5+1 +3642-14                                   4813114008L   C17
8+965-1 +5+1 +2491-14  +1240  +5+1 +1049-14                              *12  4813114009L   C17
9+1032 +811-13  +789-13  +696-13  +695-13  +647-13                            4813114010L   C17
8       +577-13  +532-13  +440-13  +318-13  +202-13                      *13  4813114011L   C17
6 +4  +4  +3  +2  +2  +1.5 +1  +1 +.925 +.535                            *14  4813114012L   C17
9 -19404697-5 +21745105-3 -75610392-2 +18509150-1 -13720012+2 4813114013L   C17
8 +46304639-6 -46365015-3 +19622565-1 -26625257-0 -87200892+1 4813114014L   C17
9 +42374904-5 -50429309-3 +12027563-1 -39402022-0 -55709250+1 4813114015L   C17
9 +54113804-5 -45220165-3 +25603121-1 -51021555+0 -35859904+1 4813114016L   C17
8 +50072609-6 -50605228-3 +22971851-1 -46725492-0 -23719838+1 4813114017L   C17
9 +10179502-6 -24352774-3 +10440446-1 -32936671-0 -16609890+1 4813114018L   C17
9 +40242709-6 -10142 79-3 +52955120-2 -27077522-0 -12659984+1 4813114019L   C17
8 +47723757-6 -56640295-4 +22101608-2 -20791540-0 -10780092+1 4813114020L   C17
9 -19992324-5 +22904120-2 -70045450-2 -82262207-1 -10270017+1 4813114021L   C17
8 -42222065-6 +50854661-3 -19602033-1 +73025737-1 -11529239+1 4813114022L   C17
9 -62724720-6 +40425 91-4 -26611952-1 -12548614+0 -22279204+1 4813114023L   C17
6+60                                                          4813114024L   C17
9 +64072101-10+10267048-5 -24561704-2 -62046463-1 -13622906+2 4813114025L   C17
8 +30425550-7 -10757600-4 +26223005-1 -11851277-0 -97630242+1 4813114026L   C17
8 +93169500-7 -22501 64-4 +22022245-2 -12566572-0 -60234616+1 4813114027L   C17
9 -45741284-7 +12550110-4 -11505706-2 -77592220-1 -50474420+1 4813114028L   C17
8 -18574762-7 +66409140-5 -70223551-3 -10254409-0 -42000229+1 4813114029L   C17
9 -76548204-7 +20822369-4 -16422432-2 -95469391-1 -32820309+1 4813114030L   C17
9 -86656242-7 +23089427-4 -17841058-2 -10333157-0 -26595781+1 4813114031L   C17
8 -79841112-7 +19543809-4 -12047281-2 -14140057-0 -15436971+1 4813114032L   C17
9 -27952590-7 +92550645-5 -36576149-3 -16992031-0 -86629181+0 4813114033L   C17
9 -62567505-7 +15706632-4 -72172791-3 -16588350-0 -29834853-0 4813114034L   C17
9 -26246272-7 +50609042-5 +27765  2-4 -17094227-0 -12608857+1 4813114035L   C17
6                                                        *15  4813114036L   C17
```

MATERIAL 14 POLYETHYLENE (CH_2) NEUTRON ENERGY
MODE 4

```
7LIBRARY DATA +1 +14 +4 +10                                                      *10 4813115001L C17
6+.1191                                                                          *11 4813115002L C17
8+206-1 +5+1 +2419-13 +213-1 +5+1 +2102-13                                           4813115003L C17
8+229-1 +5+1 +2061-13 +246-1 +5+1 +1883-13                                           4813115004L C17
8+266-1 +5+1 +1701-13 +294-1 +5+1 +1506-13                                           4813115005L C17
8+333-1 +5+1 +1301-13 +392-1 +5+1 +1081-13                                           4813115006L C17
8+492-1 +5+1 +8202-14 +604-1 +5+1 +6279-14                                           4813115007L C17
8+705-1 +5+1 +4790-14 +802-1 +5+1 +3642-14                                           4813115008L C17
8+965-1 +5+1 +2491-14 +124+0 +5+1 +1049-14                                       *12 4813115009L C17
8+10+2 +811-13 +789-13 +696-13 +685-13 +647-13                                       4813115010L C17
8      +577-13 +532-13 +440-13 +318-13 +202-13                                   *13 4813115011L C17
6 +4.05+4.06+3.225+2.23+1.495+1.005+.67+.45+.385+.43                             *14 4813115012L C17
8 -10404687-5 +21746148-3 -75610292-2 +18509150-1 -13730012+2 4813115013L C17
8 +31144442-5 -39104764-3 +16381624-1 -36732946-0 -70699864+1 4813115014L C17
8 +44245048-5 -54408821-3 +22192901-1 -47845948-0 -36599818+1 4813115015L C17
8 +34492710-5 -42981584-3 +17390818-1 -40769630-0 -21239951+1 4813115016L C17
8 +10278884-5 -24115542-3 +10179942-1 -22701097-0 -14999989+1 4813115017L C17
8 +50701084-6 -66935881-4 +21434027-2 -22954942-0 -11299945+1 4813115018L C17
8 -24495526-6 +27721213-4 -67566941-3 -17426732-0 -10400072+1 4813115019L C17
8 -15018545-5 +17462023-3 -61074723-2 -10288380-0 -10300053+1 4813115020L C17
8 -25416700-5 +29651433-3 -10651547-1 -40891163-1 -10600110+1 4813115021L C17
8 -43322905-5 +50854661-3 -18693932-1 +73025787-1 -11520239+1 4813115022L C17
8 -53734700-6 +69425281-4 -2661[illegible]-2 -12548414+0 -22279204+1 4813115023L C17
6+.60                                                                                4813115024L C17
8 +64072191-10+10367048-5 -24862704-3 -62046453-1 -13622906+2 4813115025L C17
8 -18470968-7 +58287660-5 -64564170-3 -66372397-1 -89520462+1 4813115026L C17
8 -30132018-7 +11683328-4 -11002283-2 -91338702-1 -60243797+1 4813115027L C17
8 -17714810-6 +47950532-4 -41771455-2 -55876002-3 -48881220+1 4813115028L C17
8 -71742620-7 +18995282-4 -14403268-2 -11029165-0 -29475955+1 4813115029L C17
8 -84133411-7 +21027696-4 -13985008-2 -12924120-0 -19206038+1 4813115030L C17
8 -84971164-7 +20577768-4 -12488121-2 -14243364-0 -14158306+1 4813115031L C17
8 -85060333-7 +20278256-4 -11723919-2 -14848632-0 -10839083+1 4813115032L C17
8 -80646800-7 +19044408-4 -10489057-2 -15378647-0 -81720047+0 4813115033L C17
8 -68567595-7 +15704533-4 -73172781-3 -16588359-0 -29834853-0 4813115034L C17
8 -24846272-7 +50609042-5 +27765753-4 -17096237-0 -19608857+1 4813115035L C17
6                                                                                *15 4813115036L C17
```

LIBRARY-TYPE 1

MATERIAL 15   CARBON   NEUTRON ENERGY
                                             MODE 1

```
7LIBRARY DATA +1 +15 +1 +10                                     *10  4813116001L    C17
6+.0407                                                         *11  4813116002L    C17
8      +194-1  +6+1 +2331-13 +2025-1 +6+1   +2134-13                 4813116003L    C17
8      +213-1  +6+1 +1961-13+ 2270-1 +6+1+   1783-13                 4813116004L    C17
8      +245-1  +6+1 +1600-13+ 2700-1 +6+1+   1419-13                 4813116005L    C17
8      +304-1  +6+1 +1221-13+ 3560-1 +6+1+   1007-13                 4813116006L    C17
8      +444-1  +6+1 +7606-14+ 5410-1 +6+1+   5762-14                 4813116007L    C17
8      +636-1  +6+1 +4486-14+ 7300-1 +6+1+   3513-14                 4813116008L    C17
8      +870-1  +6+1 +2379-14+ 1126+0 +6+1+   1078-14            *12  4813116009L    C17
8+10+2 +160-13  +106-13  +609-14  +682-14  +612-14                   4813116010L    C17
8       +862-14  +644-14  +424-14  +272-14  +144-14             *13  4813116011L    C17
6 +4  +4  +3  +2  +2  +1.5 +1  +1 +.825 +.565                   *14  4813116012L    C17
8 +22433999-4 -26957926-2 +10613584-0 -16947028+1 -45732995+1 4813116013L    C17
8 +18205393-4 -21712165-2 +84253106-1 -13253000+1 -34433064+1 4813116014L    C17
8 +11787230-4 -14160709-2 +55770528-1 -90566283+0 -23533166+1 4813116015L    C17
8 +90219542-5 -10811645-2 +42464096-1 -69692353+0 -18333188+1 4813116016L    C17
8 +67434826-5 -80525828-3 +31311340-1 -51050411+0 -13333238+1 4813116017L    C17
8 +39683030-5 -45994446-3 +17025798-1 -28143471-0 -86999515+0 4813116018L    C17
8 +20998260-5 -24188010-3 +87182622-2 -15642874-0 -65666470+0 4813116019L    C17
8 +18462934-5 -19897594-3 +59974741-2 -81006691-1 -47666596-0 4813116020L    C17
8 +26404461-7 -38059021-5 -62356037-3 +24483738-1 -35333393-0 4813116021L    C17
8 -88483070-6 +11080980-3 -52793049-2 +98162019-1 -37333550-0 4813116022L    C17
8 +25175057-5 -29683382-3 +10791235-1 -16391472-0 -74333048+0 4813116023L    C17
6+60                                                          4813116024L    C17
8 -12188750-9 +50192966-7 +84870175-4 -83160583-1 -10894110+2 4813116025L    C17
8 -30577138-9 +41235890-6 -15942873-3 -19470947-1 -11005524+2 4813116026L    C17
8 -39241120-9 +50637901-6 -19489380-3 -13673393-1 -76239262+1 4813116027L    C17
8 +32355989-9 -31185720-6 +94870738-4 -46536309-1 -48481075+1 4813116028L    C17
8 +10893183-9 -11754091-6 +46606780-4 -44353697-1 -32356791+1 4813116029L    C17
8 +19333410-10-12622735-7 +14965328-4 -45870640-1 -16727149+1 4813116030L    C17
8 +31820491-10-26598570-7 +27718088-4 -51756003-1 -66494975+0 4813116031L    C17
8 -12936304-9 +14564425-6 -28479823-4 -47893397-1 +16921094-0 4813116032L    C17
8 -55415856-10+11610842-6 -39963004-4 -45128531-1 +11947965+1 4813116033L    C17
8 -10555576-9 +18044354-6 -65256296-4 -42963114-1 +17558925+1 4813116034L    C17
8 -42421767-10+49451302-7 +52449185-5 -51619900-1 -12954567-0 4813116035L    C17
6                                                          *15  4813116036L    C17
```

```
    MATERIAL 16      BORON

7LIBRARY DATA +1 +16 +0 +0                                        *10  4813117001L    C17
6+.0540                                                           *11  4813117002L    C17
8+1970-1+5+1 +2278-13+1966-1+5+1 +2119-13                              4813117003L    C17
8+2061-1+5+1 +1932-13+2187-1+5+1 +1748-13                              4813117004L    C17
8+2374-1+5+1 +1585-13+2612-1+5+1 +1406-13                              4813117005L    C17
8+2946-1+5+1 +1216-13+3449-1+5+1 +1008-13                              4813117006L    C17
8+4311-1+5+1 +7696-14+5251-1+5+1 +5981-14                              4813117007L    C17
8+6177-1+5+1 +4627-14+7112-1+5+1 +3689-14                              4813117008L    C17
8+9457-1+5+1 +2534-14+1080+0+5+1 +1156-14                         *12  4813117009L    C17
8+10+2 +114-12  +682-13  +771-13  +731-13  +517-13                     4813117010L    C17
8       +264-13  +151-13  +716-14  +415-14  +223-14               *13  4813117011L    C17



    MATERIAL 17      ALUMINUM

7LIBRARY DATA +1 +17 +0 +0                                        *10  4813118001L    C17
6+.0292                                                           *11  4813118002L    C17
8+2220-1+13+2+2216-13+2320-1+13+2+2610-13                              4813118003L    C17
8+2410-1+13+2+2346-13+2490-1+13+2+2051-13                              4813118004L    C17
8+2640-1+13+2+1267-13+2820-1+13+2+1546-13                              4813118005L    C17
8+3100-1+13+2+1288-13+3530-1+13+2+1019-13                              4813118006L    C17
8+4320-1+13+2+7465-14+5240-1+13+2+5596-14                              4813118007L    C17
8+6140-1+13+2+4341-14+6940-1+13+2+3269-14                              4813118008L    C17
8+9400-1+13+2+2299-14+1120+0+13+2+1181-14                         *12  4813118009L    C17
8+10+2 +176-13  +127-13  +714-14  +500-14  +353-14                     4813118010L    C17
8       +182-14  +142-14  +985-15  +557-15  +335-15               *13  4813118011L    C17



    MATERIAL 18      IRON

7LIBRARY DATA +1 +18 +0 +0                                        *10  4813119001L    C17
6+.0214                                                           *11  4813119002L    C17
8+2940-1+26+2+3989-13+2940-1+26+2+3518-13                              4813119003L    C17
8+2950-1+26+2+3064-13+2970-1+26+2+2623-13                              4813119004L    C17
8+3040-1+26+2+2220-13+3130-1+26+2+1818-13                              4813119005L    C17
8+3300-1+26+2+1435-13+3600-1+26+2+1076-13                              4813119006L    C17
8+4240-1+26+2+7401-14+5070-1+26+2+5441-14                              4813119007L    C17
8+5950-1+26+2+4229-14+6970-1+26+2+3269-14                              4813119008L    C17
8+8280-1+26+2+2355-14+1170+0+26+2+1494-14                         *12  4813119009L    C17
8+10+2 +286-14  +969-14  +225-14  +927-15  +547-15                     4813119010L    C17
8       +380-15  +307-15  +216-15  +104-15  +467-16               *13  4813119011L    C17
```

LIBRARY-TYPE 1

MATERIAL 19   ZIRCONIUM

```
7LIBRARY DATA +1 +19 +0 +0                        *10  4813120001L   C17
6+.0150                                           *11  4813120002L   C17
8+3310-1+40+2+4614-13+3290-1+40+2+4066-13              4813120003L   C17
8+3230-1+40+2+3461-13+3090-1+40+2+2791-13              4813120004L   C17
8+2910-1+40+2+2326-13+3220-1+40+2+1930-13              4813120005L   C17
8+3280-1+40+2+1461-13+3440-1+40+2+1038-13              4813120006L   C17
8+3920-1+40+2+6760-14+4620-1+40+2+4780-14              4813120007L   C17
8+5450-1+40+2+3733-14+6420-1+40+2+3101-14              4813120008L   C17
8+7970-1+40+2+2355-14+1730+0+40+2+3921-14         *12  4813120009L   C17
6+0                                               *13  4813120010L   C17
```

MATERIAL 20   NIOBIUM

```
7LIBRARY DATA +1 +20 +0 +0                        *10  4813121001L   C17
6+.0153                                           *11  4813121002L   C17
8+3450-1+41+2+4822-13+3400-1+41+2+4196-13              4813121003L   C17
8+3360-1+41+2+3615-13+3330-1+41+2+3049-13              4813121004L   C17
8+3320-1+41+2+2509-13+3330-1+41+2+1994-13              4813121005L   C17
8+3390-1+41+2+1512-13+3550-1+41+2+1072-13              4813121006L   C17
8+4030-1+41+2+6921-14+4780-1+41+2+4957-14              4813121007L   C17
8+5600-1+41+2+3813-14+6520-1+41+2+3077-14              4813121008L   C17
8+8240-1+41+2+2443-14+1270+0+41+2+1986-14         *12  4813121009L   C17
6+0                                               *13  4813121010L   C17
```

MATERIAL 21   TUNGSTEN

```
7LIBRARY DATA +1 +21 +0 +0                                *10  4813122001L   C17
6+.0102                                                   *11  4813122002L   C17
8+4650-1+74+2+6824-13+4490-1+74+2+5854-13                      4813122003L   C17
8+4380-1+74+2+5000-13+4270-1+74+2+4170-13                      4813122004L   C17
8+4180-1+74+2+3412-13+4090-1+74+2+2675-13                      4813122005L   C17
8+4020-1+74+2+1993-13+4050-1+74+2+1379-13                      4813122006L   C17
8+4320-1+74+2+8523-14+5100-1+74+2+6278-14                      4813122007L   C17
8+6400-1+74+2+5671-14+8400-1+74+2+5866-14                      4813122008L   C17
8+1250+0+74+2+6320-14+5050+0+74+2+1746-13                 *12  4813122009L   C17
8+10+2  +336-15  +273-15  +202-15  +857-15  +952-15            4813122010L   C17
8       +115-15  +749-16  +450-16  +268-16  +126-16       *13  4813122011L   C17
```

```
   MATERIAL 22        LEAD

7LIBRARY DATA +1 +22 +0 +0                              *10   4813122001L   C17
6+.01[illegible]                                        *11   4813122002L   C17
[illegible]                                                   4813122003L   C17
[illegible]                                                   4813122004L   C17
[illegible]                                                   4813122005L   C17
[illegible]                                                   4813122006L   C17
[illegible]                                                   4813122007L   C17
[illegible]                                                   4813122008L   C17
[illegible]                                             *12   4813122009L   C17
6+0                                                     *13   4813122010L   C17


   MATERIAL 23        URANIUM

7LIBRARY DATA +1 +23 +0 +0                              *10   4813124001L   C17
6+.00[illegible]                                        *11   4813124002L   C17
[illegible]                                                   4813124003L   C17
[illegible]                                                   4813124004L   C17
[illegible]                                                   4813124005L   C17
[illegible]                                                   4813124006L   C17
[illegible]                                                   4813124007L   C17
[illegible]                                                   4813124008L   C17
[illegible]                                             *12   4813124009L   C17
6+0                                                     *13   4813124010L   C17


   MATERIAL 24        LITHIUM HYDRIDE POLYETHYLENE MATRIX
                      CONSTITUENTS  (BY WEIGHT)
                      LITHIUM HYDRIDE        .80
                      POLYETHYLENE           .20

7LIBRARY DATA +1 +24 +0 +0                                        *10   4813125001L   C17
6+.144                                                            *11   4813125002L   C17
8+192-01 +2+1 +2100-12 +132-01  +3+1 +1950-13                           4813125003    C17
8+206-01 +2+1 +1224-12 +221-01  +3+1 +1672-13                           4813125004    C17
8+247-01 +2+1 +1567-12 +260-01  +3+1 +1376-13                           4813125005    C17
8+308-01 +2+1 +1207-12 +362-01  +3+1 +1007-13                           4813125006    C17
8+458-01 +2+1 +7770-14 +562-01  +3+1 +6025-14                           4813125007    C17
8+657-01 +2+1 +4566-14 +754-01  +3+1 +3574-14                           4813125008    C17
8+999-01 +3+1 +3055-14 +1172+0  +3+1 +1161-14                     *12   4813125009L   C17
8+10+2 +199-12  +197-12  +933-13  +294-13  +831-13                      4813125010L   C17
8      +667-13  +572-13  +449-13  +302-13  +204-13                *13   4813125011L   C17
```

LIBRARY-TYPE 1

```
MATERIAL 25        BORAL
                   CONSTITUENTS  (BY WEIGHT)
                   BORON CARBIDE          .23
                   ALUMINUM               .77

*LIBRARY DATA +1 +25 +0 +0                                      *10  4813126001L   C17

[illegible]+.0046                                               *11  4813126002L   C17
9+2200-1+13+2+2772-13+2250-1+13+2+2498-13                            4813126003L   C17
9+1220-1+13+2+2262-13+2420-1+13+2+1024-13                            4813126004L   C17
9+2620-1+13+2+1767-13+2760-1+13+2+1614-13                            4813126005L   C17
9+2070-1+13+2+1272-13+2620-1+13+2+1013-13                            4813126006L   C17
9+4320-1+13+2+7514-14+5260-1+13+2+5655-14                            4813126007L   C17
9+4160-1+13+2+4400-14+6090-1+13+2+3367-14                            4813126008L   C17
9+4430-1+13+2+2345-14+1110+0+13+2+1171-14                       *12  4813126009L   C17
9+10+2 +340-13   +226-13   +197-13   +176-13   +123-13               4813126010L   C17
9         +650-14   +413-14   +226-14   +141-14   +731-15       *13  4813126011L   C17



MATERIAL 26        BORON CARBIDE

*LIBRARY DATA +1 +26 +0 +0                                      *10  4813127001L   C17
6+.0511                                                         *11  4813127002L   C17
9+2160-1+5+1  +4325-13+3290-1+5+1  +4009-13                          4813127003L   C17
9+3470-1+5+1  +2731-13+3710-1+5+1  +3441-13                          4813127004L   C17
9+4020-1+5+1  +3162-13+4500-1+5+1  +2003-13                          4813127005L   C17
9+5010-1+5+1  +2525-13+5570-1+5+1  +2152-13                          4813127006L   C17
9+7220-1+5+1  +1797-13+9900-1+5+1  +1270-13                          4813127007L   C17
9+1058+0+5+1  +1156-13+1213+0+5+1  +2640-14                          4813127008L   C17
9+1432+0+5+1  +7201-14+1561+0+5+1  +4190-14                     *12  4813127009L   C17
6+0                                                             *13  4813127010L   C17
```

```
MATERIAL 27        ZIRCONIUM HYDRIDE (ZrH1.5)

*LIBRARY DATA +1 +27 +0 +0                                      *10  4813128001L   C17
6+.0004                                                         *11  4813128002L   C17
9+2210-1+37+2+4614-13+3290-1+37+2+4052-13                            4813128003L   C17
9+3240-1+29+2+3461-13+2120-1+29+2+2225-13                            4813128004L   C17
9+2040-1+30+2+2264-13+2250-1+32+2+1022-13                            4813128005L   C17
9+2320-1+29+2+1474-13+2500-1+35+2+1052-13                            4813128006L   C17
9+4000-1+30+2+6820-14+4700-1+32+2+4647-14                            4813128007L   C17
9+5570-1+29+2+3813-14+6520-1+28+2+2107-14                            4813128008L   C17
9+9120-1+29+2+2355-14+1400+0+29+2+25[illegible]-14              *12  4813128009L   C17
6+0                                                             *13  4813128010L   C17
```

YPE 1

GHT)
90
06
04

	*10	4813129001L	C17
	*11	4813129002L	C17
3		4813129003L	C17
3		4813129004L	C17
3		4813129005L	C17
3		4813129006L	C17
4		4813129007L	C17
4		4813129008L	C17
4	*12	4813129009L	C17
	*13	4813129010L	C17

GHT)
755
232
013

*10	4813130001L	C17
*11	4813130002L	C17

YPE 1

HT)
ON .3135
ER .0012
SIUM .0192
UM .0826
.0122

*10	4813131001L	C17
*11	4813131002L	C17
	4813131003L	C17
	4813131004L	C17
	4813131005L	C17
	4813131006L	C17
	4813131007L	C17
	4813131008L	C17
*12	4813131009L	C17
*13	4813131010L	C17

HT)
ER .105
UM .045
.044
) .446

*10	4813132001L	C17
*11	4813132002L	C17
	4813132003L	C17
	4813132004L	C17
	4813132005L	C17
	4813132006L	C17
	4813132007L	C17
	4813132008L	C17
*12	4813132009L	C17
*13	4813132010L	C17

```
MATERIAL 32      MAGNETITE CONCRETE
                 CONSTITUENTS  (BY WEIGHT)
    HYDROGEN           .008      ALUMINUM           .014
    CARBON             .001      SILICON            .126
    OXYGEN             .395      POTASSIUM          .004
    SODIUM             .005      CALCIUM            .039
    MAGNESIUM          .001      IRON               .407

7LIBRARY DATA +1 +32 +0 +0                             *10  4813133001L    C17
6+.0329                                                *11  4813133002L    C17
8+2630-1+16+2+3460-13+2670-1+16+2+3115-13                   4813133003L    C17
8+2750-1+16+2+2782-13+2850-1+16+2+2466-13                   4813133004L    C17
8+2980-1+16+2+2143-13+3170-1+17+2+1826-13                   4813133005L    C17
8+3450-1+18+2+1512-13+3910-1+16+2+1202-13                   4813133006L    C17
8+4750-1+18+2+8843-14+5720-1+19+2+6675-14                   4813133007L    C17
8+6740-1+20+2+5319-14+7650-1+19+2+4135-14                   4813133008L    C17
8+9280-1+18+2+3020-14+1330+0+17+2+2030-14              *12  4813133009L    C17
6+0                                                    *13  4813133010L    C17


MATERIAL 33      MAGNETITE CONCRETE WITH IRON PUNCHINGS
                 CONSTITUENTS  (BY WEIGHT)
    HYDROGEN           .004      SILICON            .018
    OXYGEN             .194      CALCIUM            .029
    MAGNESIUM          .001      IRON               .751
    ALUMINUM           .003

7LIBRARY DATA +1 +33 +0 +0                             *10  4813134001L    C17
6+.0271                                                *11  4813134002L    C17
8+2750-1+24+2+3664-13+2760-1+24+2+3302-13                   4813134003L    C17
8+2800-1+24+2+2872-13+2850-1+24+2+2477-13                   4813134004L    C17
8+2940-1+24+2+2115-13+3060-1+24+2+1754-13                   4813134005L    C17
8+3260-1+24+2+1403-13+3610-1+24+2+1076-13                   4813134006L    C17
8+4310-1+24+2+7593-14+5140-1+23+2+5552-14                   4813134007L    C17
8+6070-1+22+2+4373-14+6920-1+23+2+3378-14                   4813134008L    C17
8+8410-1+23+2+2427-14+1250+0+23+2+1786-14              *12  4813134009L    C17
6+0                                                    *13  4813134010L    C17
```

LIBRARY-TYPE 1

```
MATERIAL 34      GROUND TEST REACTOR CORE MATERIAL
                 CONSTITUENTS  (BY WEIGHT)
                 WATER               .329
                 ALUMINUM            .649
                 URANIUM             .022

7LIBRARY DATA +1 +34 +0 +0                                   *10   4813135001L    C17
6+.0544                                                      *11   4813135002L    C17
8+2320-1+12+2+2964-13+2370-1+12+2+2668-13                          4813135003L    C17
8+2460-1+12+2+2410-13+2560-1+12+2+2130-13                          4813135004L    C17
8+2720-1+12+2+1884-13+2920-1+12+2+1618-13                          4813135005L    C17
8+3220-1+22+2+1358-13+3690-1+12+2+1091-13                          4813135006L    C17
8+4530-1+14+2+8106-14+5490-1+17+2+6124-14                          4813135007L    C17
8+6470-1+26+2+4838-14+7370-1+25+2+3762-14                          4813135008L    C17
8+9020-1+24+2+2779-14+1290+0+24+2+1846-14                    *12   4813135009L    C17
6+0                                                          *13   4813135010L    C17
```

LIBRARY-TYPE 2

```
7LIBRARY DATA+2+3+2                                            *16   4813101001L   C17
6+10+9+8+7+6+5+4+3+2+1.375+1+.75+.5+.25                              4813101002L   C17
6+10+9+8+7+6+5+4+3+2+1.375+1+.75+.5                                  4813101003L   C17
8+1-1+9124-2+8347-2+753-2+6707-2+5858-2+4985-2+4075-2+3058-2         4813101004L   C17
8+2318-2+1797-2+1405-2+9551-3+4533-3                           *17   4813101005L   C17
8+26+2+221189-8-447035-7-596629-9-462254-1+605384-3-647380+0         4813101006L   C17
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LIBRARY-TYPE 2 (cont'd.)

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8     -893241-4+181801-2+113065-4+253329-2-193827-4-192197+0      4813101358L   C17
8     -835952-4+253777-2-189964-5+451219-2-256598-4-232930+0      4813101359L   C17
8     -713537-4+201501-2+696360-6+552279-2-339028-4-264074+0      4813101360L   C17
8     +354162-4-119069-2+140169-4+756672-2-519074-4-311262+0      4813101361L   C17
6                                                             *20 4813101362L   C17
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